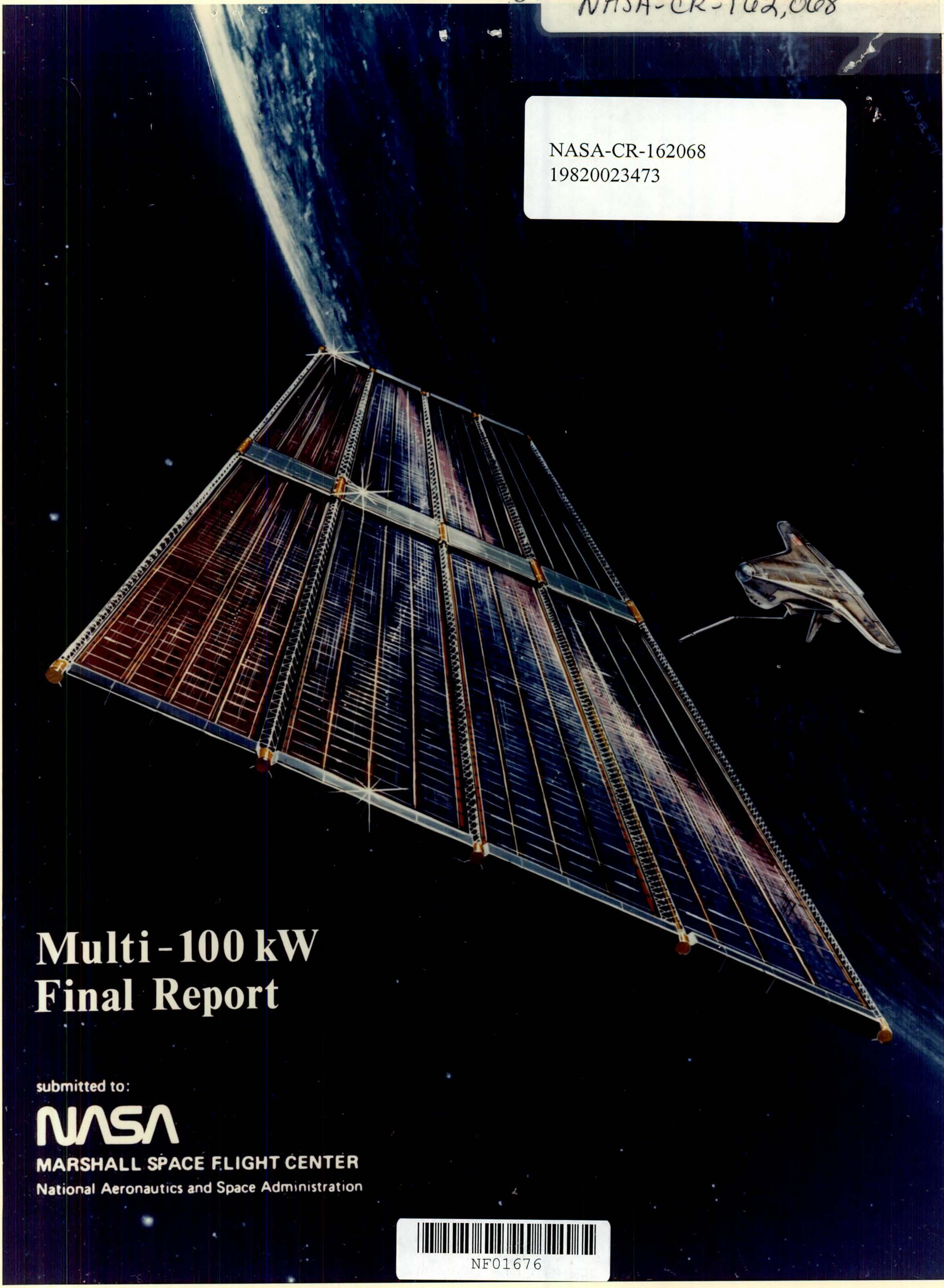
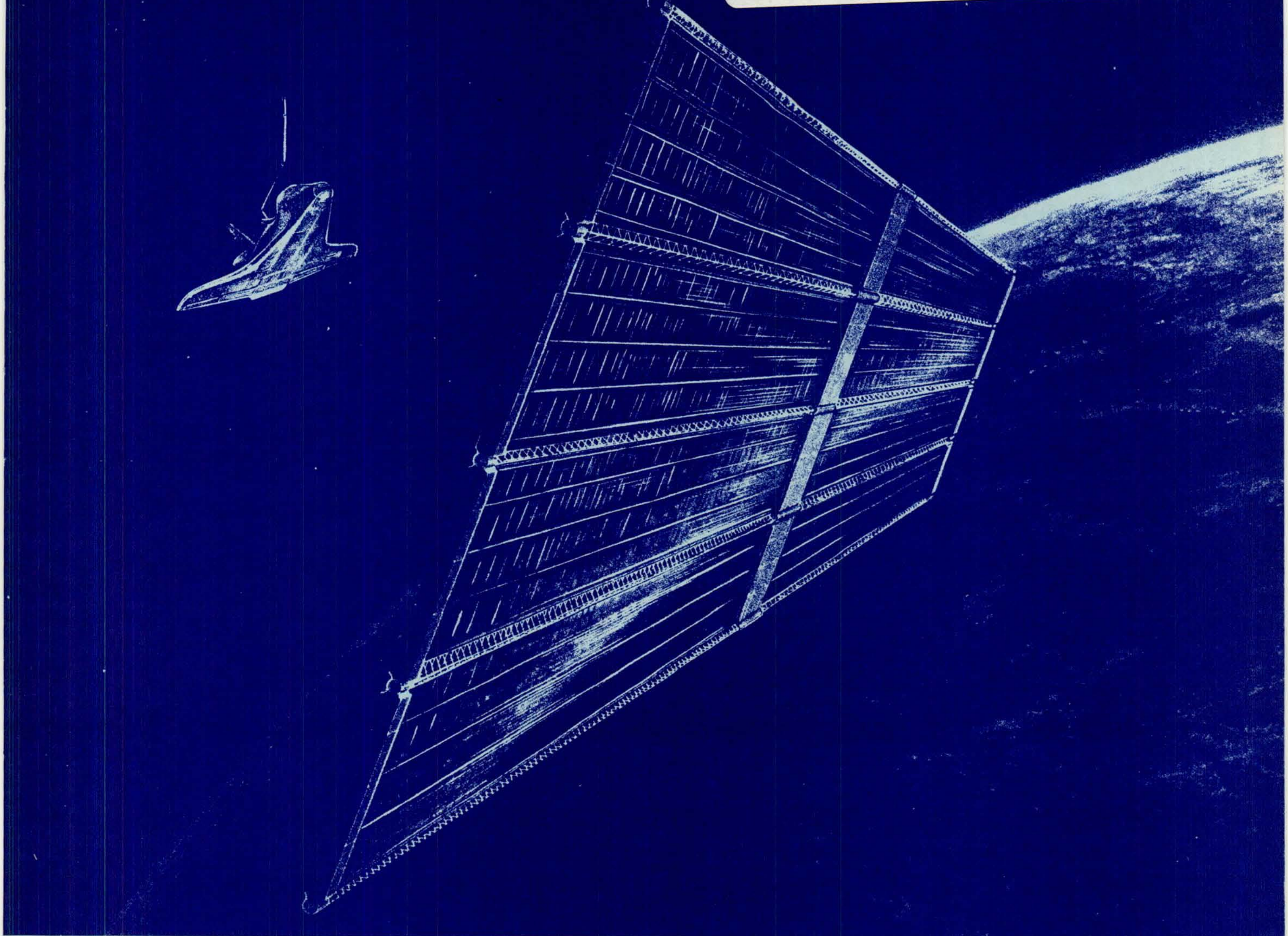


Multi-100 kW Final Report

submitted to:

NASA
MARSHALL SPACE FLIGHT CENTER
National Aeronautics and Space Administration

NASA-CR-162,068



Final Report

June 1982

Multi-100 kW Planar

Planar Low Cost Solar Array Development

submitted to:

NASA

MARSHALL SPACE FLIGHT CENTER
National Aeronautics and Space Administration

Lockheed

MISSILES & SPACE COMPANY, INC. SUNNYVALE, CALIFORNIA

FOREWORD

This report documents the work performed by Lockheed Missiles & Space Co., Inc., Sunnyvale, California, for Marshall Space Flight Center of the National Aeronautics and Space Administration under contract no. NAS8-32981 on the Multi-100 kW Planar, Low-Cost Solar Array Development project.

The term of this contract was 9 months beginning on 1 September 1981 and concluding on 31 May 1982. However, due to late cell deliveries a no-cost extension was requested and granted, and the contract was extended through 31 July 1982. This report summarizes the full term effort performed on the subject contract over this entire period.

G. Smith of the Astrionics Laboratory, Power Systems Branch of NASA/MSFC, provided technical direction for this work.

CONTENTS

CONTENTS (Cont.)

LIST OF FIGURES

LIST OF TABLES

1.0 BACKGROUND

1.1 OBJECTIVES

The operational success of the Space Shuttle, coupled with the upcoming launch of the lightweight, large area, flexible Solar Array Flight Experiment (SAFE), bring into reality the possibility of placing into space within the next few years a variety of experiments with expectations of large power system capability. It is now feasible to envision self-erecting Multi-100 kW systems or acres of array deployed over large in-space constructed beam structures. The engineer thinking in these terms can focus on the essentials of accomplishing such a task. The primary considerations must be cost, weight, simplicity of sub-components and assemblies; availability of materials; and long term operational capability.

The previous contract concentrated on identifying low cost blanket designs, evaluating materials, simplified assembly techniques, single sheet glassing of multiple cells and some advanced cell considerations. The contract outcome was the design and fabrication of 4 blanket assemblies varying in complexity, in order to verify the cost saving assumptions that were made.

Lack of certain materials allowed only the demonstration of the concept and not the actual verification. For instance, cell costs can only be estimated since large quantities of these cells have never been produced.

The focal point of this contract was directed at the least complex of the 4 designs which featured the superstrate concept and lower cost versions of the large area solar cell. Large area cell coverage by a single coverglass sheet and large area cells with gridded backside contacts lowering α were shown by the previous study to reduce assembly and material costs by 20% over conventional single cell glassing and full contact backside contact designs.

Thus, the overall objective was to demonstrate that the estimated costs could be realized by actually fabricating modular hardware. Briefly, the objectives were as follows:

Task 1.

- Develop and negotiate a simplified large-area solar cell specification
- Purchase large-area wraparound contact silicon cells representing low-cost alternatives
- Investigate the potential of even larger cells (10 x 10 cm) for further cost reduction

Task 2.

- Conduct cell level electrical, mechanical and rapid thermal cycle tests
- Fabricate 4-cell and 30-cell modules
- Conduct module electrical and thermal cycle tests

1.2 GUIDELINES

General guidelines were provided which formed the basis for the approach taken. These guidelines were as follows:

- Investigate specific areas where significant cost advantages are possible (superstrate vs single cell glass covering, minimize process steps as well as cleanup, etc.)
- Evaluate significance of silver buildup by evaporation vs plating as method of reducing contact metallization cost
- Compare relative to contact pull strength and thermal cycling effect
- Evaluate practicality of replacing silver with lower cost copper
- Develop a simplified specification with cell vendor
- Consider large area solar cells with investigation into cells up to 10 x 10 cm
- Recommend purchase of cells from ASEC, Spectrolab, and Spire Corp.

Reporting

This contract required one midterm and one final oral presentation and the submittal of a final written report. Program statusing was accomplished by monthly reporting. The basic contract was amended to incorporate LMSC's proposal to fabricate a 14" x 16" 30-cell superstrate for delivery to NASA in lieu of the midterm oral, due to late cell delivery.

All effort including analysis, conceptual descriptions, manufacturing details, test results, cost data, assessments of modules fabricated and recommended technology for a follow-on contract are included in this final report.

Delivery

Ten 4-cell modules representing conventional wraparound 5.9 x 5.9 cm, copper contact and silver backside, gridded silicon solar cells will be delivered to NASA. These will be a mix of 5 superstrates and 5 conventional cell-blanket substrate assemblies. In addition, a 30-cell superstrate shall be delivered. Solar cells, particularly the copper contacted cells, that were delivered were not of the highest quality as had been anticipated. The wraparound procedure proved to require more development before copper adhesion could be guaranteed and junction poisoning eliminated. As such, the copper cells delivered in 4-cell modules are not representative of what should be expected from copper. Contact adhesion was also generally poor on the gridded backside contact cells. Process control was lacking as the new rotating cage used for mounting and rotating the cells during production evaporation was not completed; thus these cells were made under rather outdated techniques in an older evaporation chamber.

1.3 SCHEDULE

The term of this contract follow-on was a 9 month period from 1 September 1981 to 31 May 1982. On 5 May 1982, LMSC requested a no-cost extension of 30 days to allow for late cell delivery of improved copper cells and 40 gridded backside contact cells for the large area module. The contract was extended through 31 July 1982. All major tasks and subtasks are shown in Figure 1-1.

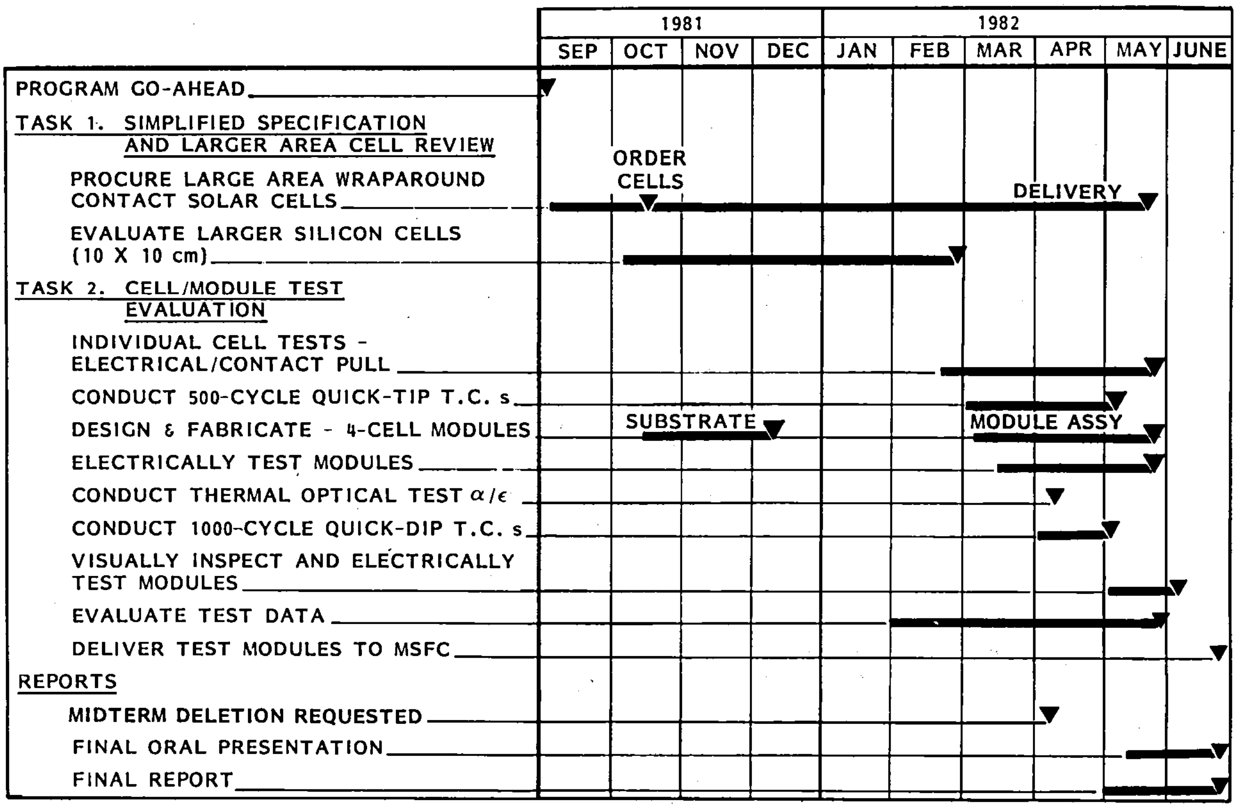


Figure 1-1 Multi-100 kW Planar Low Cost Solar Array Schedule

1.4 PROJECT ORGANIZATION

The Lockheed team was formed from experienced members of the Electrical Power Systems group managed by Larry G. Chidester. The Multi-100 kW Planar, Low Cost Solar Array Development project was managed by Jerry Mann with George Pack as Technology Task Leader, Dan Lott as Large Area Solar Cell consultant, and John Young as module designer. The project organization is shown in Figure 1-2. This team has been intact during the entire contract to ensure proper continuity. Other in-house technical and manufacturing specialists were used as necessary throughout the study term.

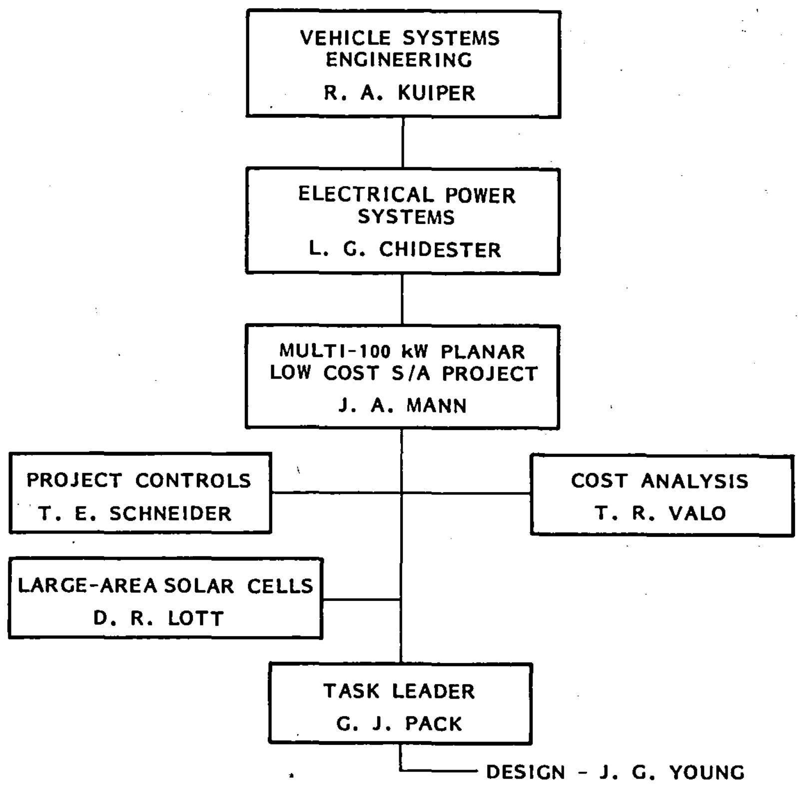


Figure 1-2 Project Organization

1.5 PROJECT WORK FLOW DIAGRAM

Prior to initiating this contract a Project Work Flow Diagram was developed as shown in Figure 1-3. Technical and NASA-directed inputs from previous Multi-100 kW Low Cost Planar contracts have been factored into LMSC input and module design blocks. The diagram is intended to show cell flow and distribution from cell vendor interface to module buildup, test and delivery. Large cell evaluation was basically independent from the 5.9 x 5.9 cm wraparound cell-module test program and is reported on separately.

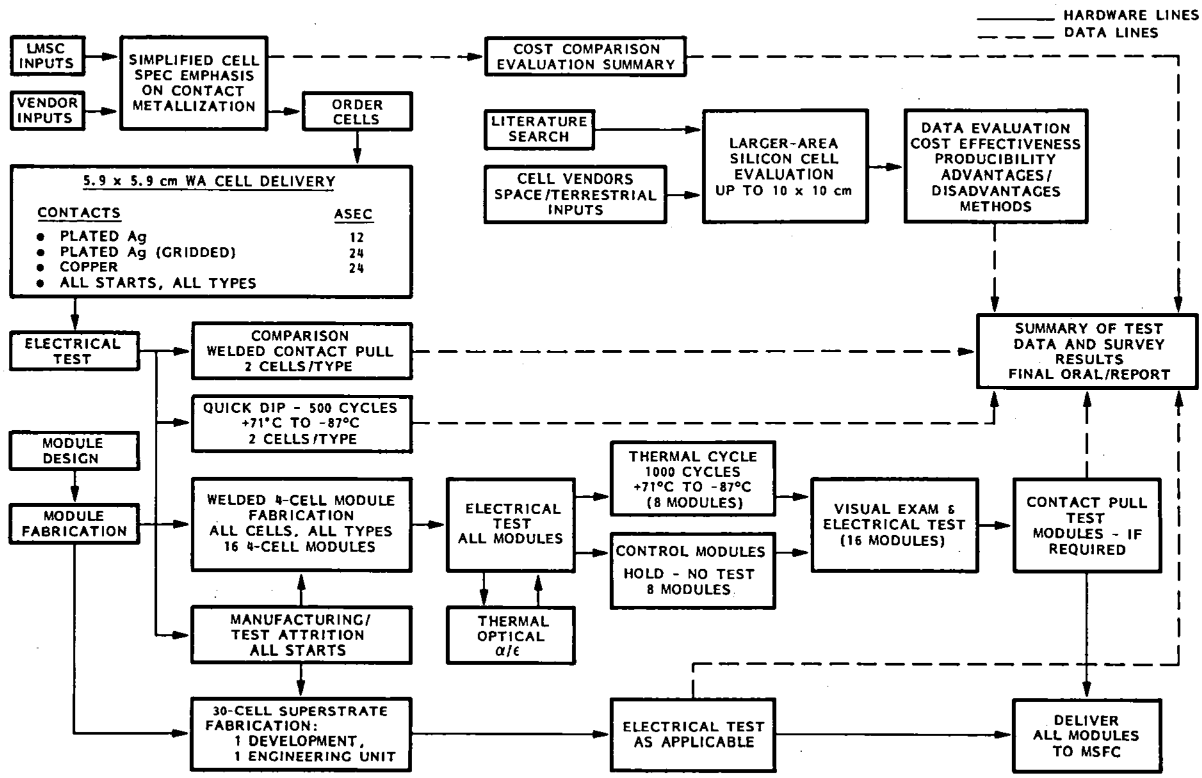


Figure 1-3 Project Work Flow Diagram

1.6 SUMMARY

The purpose of this project was to verify the applicability of selected low cost options to solar array blanket design by fabricating representative modules and submitting them to thermal cycle environment. Large area (5.9 x 5.9 cm) solar cells of 3 varieties were purchased: 1) Standard wraparound, 2) Copper contacts substituted for the conventional Titanium-Palladium-Silver, and 3) Standard wraparound except with gridded back contact instead of continuous metallization. The baseline cell was purchased to compare fabrication cost and to serve as a control cell during test evaluation of the other two cells.

All cells were assembled into either substrate modules where the cell is individually filtered and welded to an integrated Kapton-copper circuit or into a superstrate configuration with 4 cells jointly adhered to a single sheet of microsheet and then welded to the integrated Kapton-copper circuit.

The cells delivered were all from ASEC, as Spectrolab was unable to supply a dielectric wraparound cell and Spire Corp. chose to no bid the program. Cell quality, particularly in the metallization of contacts, was less than desired. The previously-proven evaporation equipment and processing that was specifically designed for wraparound cell metallization was not available during the span of this program. As such, older, less reliable, techniques had to be employed which resulted in less than desireable contact pull strengths on both the copper and the gridded cells. ASEC had further problems with copper metallization in laying down a barrier metal which would ohmically bond to the silicon and was non-porous to copper. As copper is highly mobile, even at temperatures below sintering temperature, it will migrate to the cell junction if the barrier is inadequate. The cells received were shunted (sintered) or with low contact pull strength (non-sintered), thus leading to the decision to solder rather than weld the copper cells to the Kapton substrate.

Sixteen (16) modules of superstrate and substrate mixture were fabricated and 8 5-substrate and 3-superstrate were thermal cycled for 1060 cycles at temperatures from -73°C to +87°C. "N" contacts failed in all 4 of the backside gridded cells at the metallization-silicon interface, rather than in the silicon or copper interconnect, as is typical when quality cell metallization exists. Thus the contact failure was due to poor cell metallization process control rather than thermal cycling.

Module degradation was within expected range for all cells where metallization was properly processed (~1%). Where metallization failed or signs of failure were occurring, degradation ranged from 5 to 100% or open circuit. When the cells were forced back to make contact with the circuit, degradations of 7 to 10% were measured, evidencing a high series resistance at the contact interface. Again, it should be noted that due to poor initial metallization integrity, thermal cycling greatly accelerated the contact failure. Similar test conditions and module configurations have exceeded 25,000 cycles with negligible mechanical or electrical degradation.

The theory of transmitting the non-responsive long wavelengths through the cell by using a gridded backside contact cell was confirmed with an average α of .66 and a low value of .62. This is compared to the baseline and copper cell with an α of .714. In more meaningful terms, the gridded back contact cell will operate 18°C lower temperature than the baseline cell.

An equivalent efficiency improvement would be from 12.8% to 13.4%. It is now recognized that there were insufficient funds to properly develop the copper metallization process and adapt it to the wraparound concept. Time did not allow for the development of bonding technique and schedule between the copper cell and the copper substrate. The existing weld schedule/process was tried and a bonding did occur, however, the pull strength and quality of the bond was not evaluated. It is not the intention of this report to discredit the use of copper in this application, but rather to emphasize that with adequate development it may yet be a valuable contributor to low cost solar arrays.

All cell starts, mechanicals and low output electricals were requested by Lockheed to accompany the specification cells. These extra cells were used in the construction of 2 30-cell superstrates--1 as the engineering development unit and 1 as the unit to be delivered to MSFC. Stress cracks continue to plague the superstrate; several reasons seem to be predominant. They are: small inclusions in the adhesion or scrim cloth, and small stress points in the glass sheet and along the unannealed edge after the scribe and break step required to size the sheet. However, even though the cracks are obvious to the eye, they do not affect performance nor do they progress into the solar cell itself.

Extra care to inspect adhesive, glass and scrim cloth and clean components prior to assembly did result in a near perfect 30-cell deliverable superstrate module, except for two minor edge cracks. This demonstrated that the superstrate glass cracking problem which occurs during assembly can be minimized and perhaps resolved by proper process and material control.

Tables 1-1 and 1-2 provide a description of the makeup, process and test of the 4-cell and 30-cell modules fabricated under this contract.

TABLE 1-1
4-CELL MODULE DESCRIPTION

MODULE NO.	TYPE OF CELL	CONFIGURATION SUBSTRATE[a]	CONFIGURATION SUPERSTATE[b]	WELDED	SOLDERED	THERMAL CYCLED	DISPLAY ONLY
STD - M1	BASELINE		X	X		NO	
M2	2 Ω-cm		X	X		YES	
M3	BSR		X	X		YES	
2MG	Ti-Pd-Ag	X		X		YES	
3MG	WRAPAROUND	X		X		YES	
1D	CONTACT		X	X		NO	X
GC - M1	GRIDDED CONTACT						
	2 Ω-cm		X	X		YES	
1MG	Ti-Pd-Ag	X		X		NO	
2MG	GRIDDED	X		X		YES	
3MG	BACKSIDE	X		X		YES	
4MG	WRAPAROUND	X		X		YES	
1D	CONTACT		X	X		NO	X
CC - 1	COPPER CONTACT						
	2 Ω-cm		X		X	NO	
2	Ti-Pd-Cu		X		X	NO	
3	BSR	X			X	NO	
4	WRAPAROUND	X			X	NO	
5	CONTACT	X			X	NO	

(a) INDIVIDUAL COVERS 6-mil 0211 MICROSHEETS UV AND AR COATINGS.

(b) SINGLE 6-mil 0211 MICROSHEET GLASS.

TABLE 1-2
30-CELL SUPERSTRATE DESCRIPTION

MODULE	CELL TYPE	0211 UNCOATED GLASS THICKNESS	ADHESIVE	DISPOSITION
30M - 1 D	30 0211 Covers Only	9 mil	GT-100	Engineering
-2 E	12 Std, 6 Gridded, 12 Copper	6 mil	GT-100	Engineering
-3	30 Gridded Backside contacts	9 mil	GT-100	Delivered to MSFC

Multi-100 kW

Planar Low Cost Solar Array Development

Final Report

2.0 TASK 1. LARGE AREA SOLAR CELL DESCRIPTION

2.1 SOLAR CELLS PURCHASED

During the previous phase of this contract, it was noted that substantial cost savings on the systems level would be realized if relatively minor changes in cell thermo-physical properties and materials were incorporated in the baseline cell design. By reducing the operating temperature of the array through a reduction in solar absorptance (α) or an increase in IR emittance (ϵ) of the cell, it was analytically shown that a potential existed for an approximately 0.5%, first order, system level cell cost reduction for each degree change in temperature or an overall systems cost reduction of 6%. In addition, the cost of cell metallization was identified as a major fraction of the individual cell cost. Consequently, two modifications of the baseline 5.9 x 5.9 cm cell were proposed for preliminary testing--gridding the back contact to reduce α and changing the conductor material on the cell from silver to copper. Each of the three cell types was purchased and is shown in Figures 2-1 through 2-3.

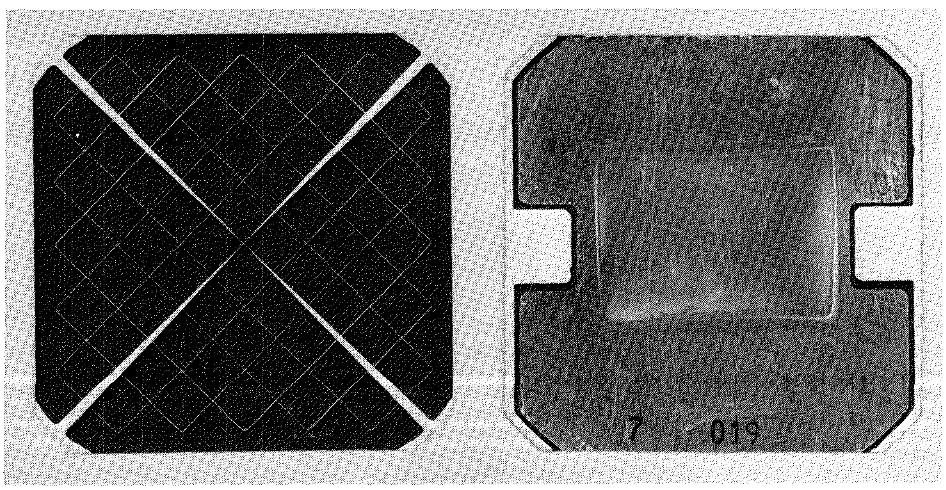


Figure 2-1 5.9 x 5.9 cm Dielectric Wraparound Silicon Solar Cell

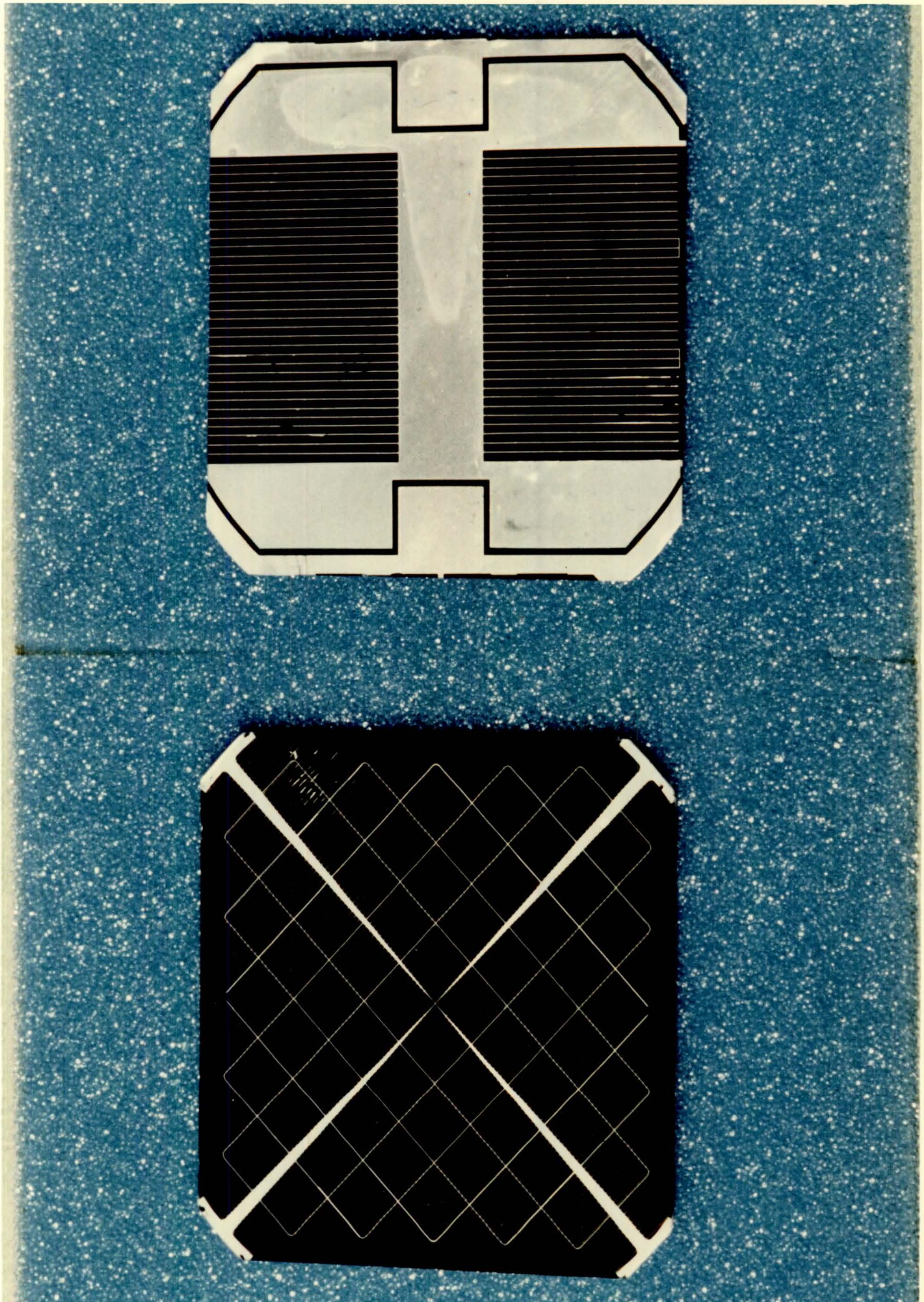


Figure 2-2 5.9 x 5.9 cm DWA Gridded Backside Contact

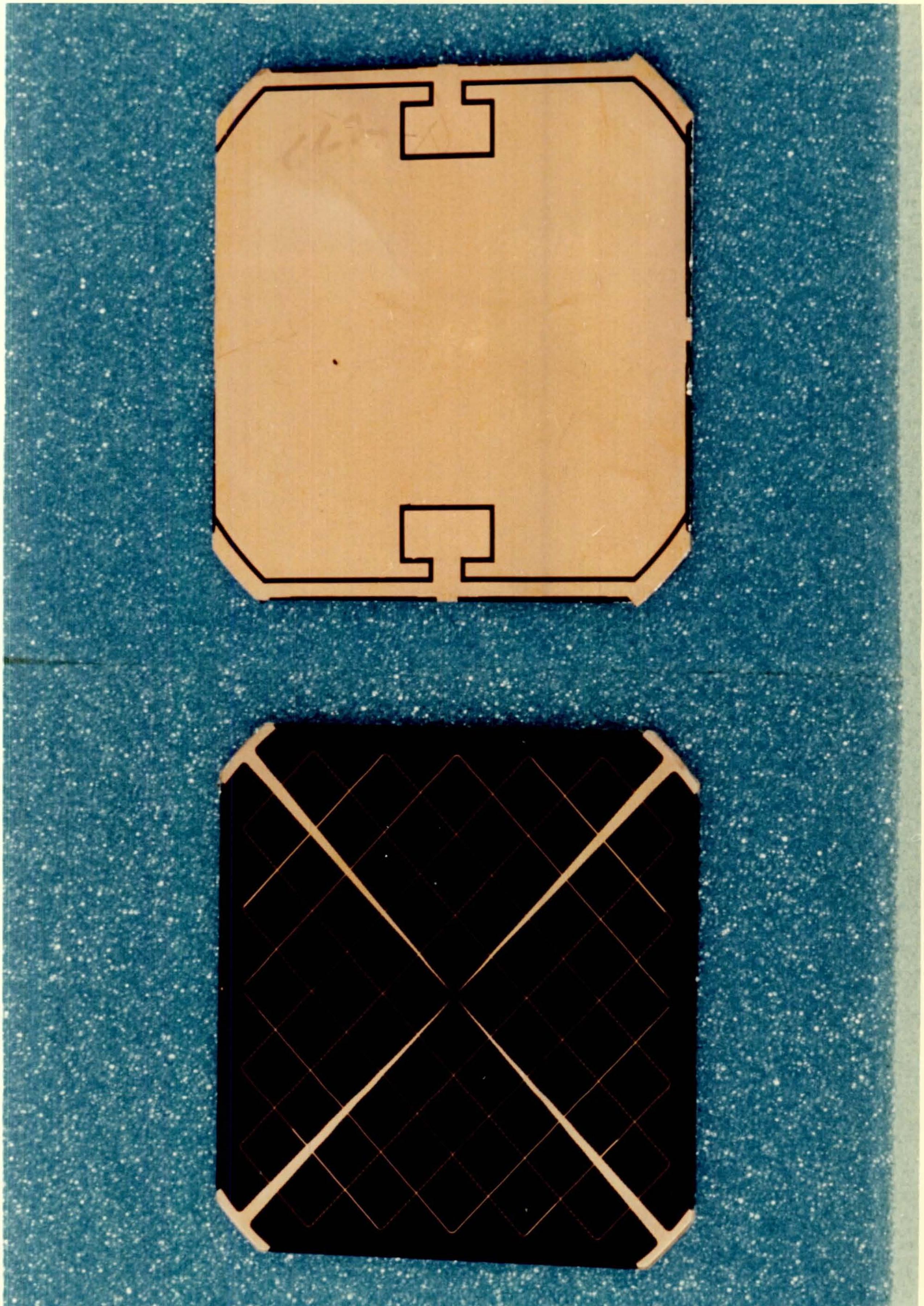


Figure 2-3 5.9 x 5.9 cm DWA Copper Contact

The baseline large area dielectric wraparound (DWA) cell has been under development for the last few years, supported by a combination of LMSC ID and NASA funding. Starting with a 3" diameter wafer, the cell size was optimized to provide the lowest cost at the systems level. Advanced processing procedures including photolithographic techniques for defining the contact metallization area, chemical vapor deposition (CVD) of an insulating edge layer to allow an edge contact wraparound and plating up to final contact thickness have resulted in a cell which promises lower total systems cost.

The gridded back contact cell is a modification of the baseline cell which takes full advantage of the proposed superstrate systems design and/or a transparent substrate. By replacing the aluminum backside reflector (BSR) and full-back contact with a gridded contact, unusable incident illumination in the 1 to 4 μ range is transmitted through the cell and rejected. This reduces the path length in the cell travelled by this unwanted light, minimizing scattering and bulk absorption losses. An additional feature is the reduced material cost associated with the reduced metal area.

During this preliminary design and concept verification phase, no attempt was made to optimize the grid structure on the back. A light boron diffusion of the back surface was included in the cell processing to increase the collection efficiency by reducing the resistivity. Future development work will be required to quantify the effect of the boron diffusion and to optimize the grid structure for low α and high cell efficiency.

Changing the contact metallization from an AlTiPdAg configuration to a lower cost TiPdCu contact resulted in processing difficulties. The choice of copper as a contacting material was the result of an LMSC study of the metallization costs and a literature survey of terrestrial cell development results. It was initially expected that a simple substitution of materials would result in an efficient, cost effective cell. However, due to the gridline size and DWA configuration, several difficulties were encountered resulting in poor performance or unacceptable contact adhesion.

The primary difficulty encountered was an inability to achieve an effective diffusion barrier to the copper. Current cell processing uses a photolithographic mask to define the contact metallization areas followed by vacuum deposition of titanium,

palladium and a thin flash of silver. After this thin metallizing step, the cells are placed in a plating solution to achieve the final contact thickness, then sintered for good contact adhesion. A similar procedure was used for the copper cells, simply substituting copper for silver. Two difficulties arose with this procedure. Standard terrestrial practice when using copper is to place a nickel barrier layer between the copper and silicon to prevent copper migration into the junction region. Due to processing concerns associated with the DWA step, the standard nickel plating process is unusable. However, even with the addition of the nickel it appeared that the copper plated on would still be able to migrate around the edge due to the method of masking and plating. In processing the 5.9 DWA cell, it is necessary to remove the photomask immediately after the vacuum deposition step before plating. When used with copper, the plated material grows on the sides of the vacuum deposited material and in contact with the silicon, leading to a diffusion problem. Figure 2-4 illustrates this process.

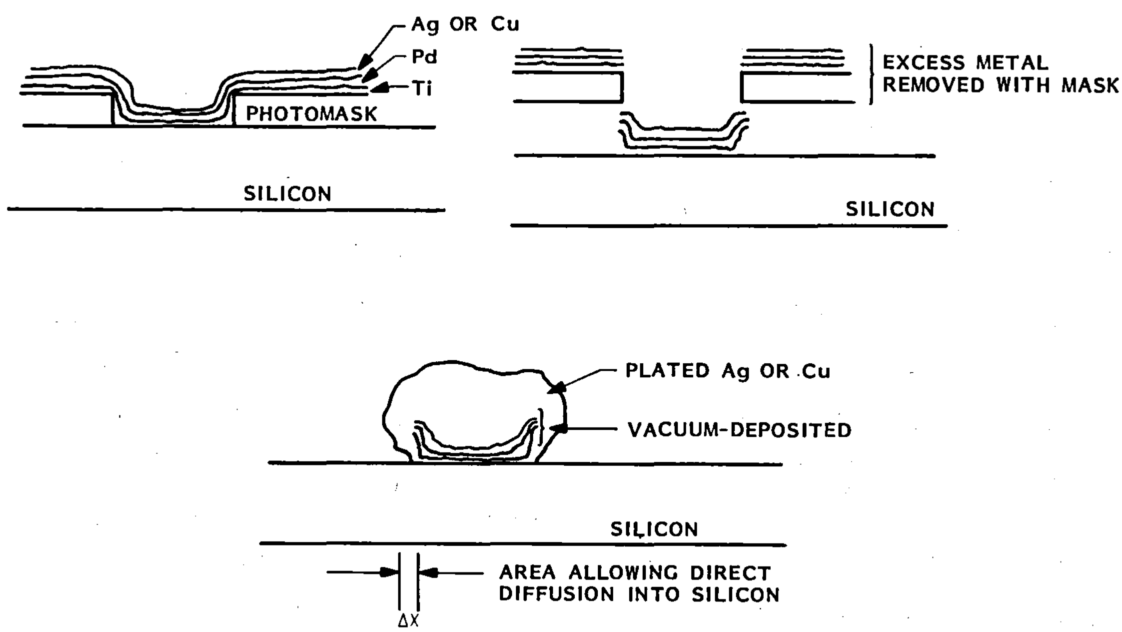


Figure 2-4 Conventional Etching Procedure

In an effort to solve this problem, a new masking technique was tried using a reverse etch procedure. Under this technique, the entire wafer is metallized, the mask applied and undesirable material removed. This method was unsuccessful because the gridline width is of the same order as the metal thickness resulting in total metal removal (see Figure 2-5).

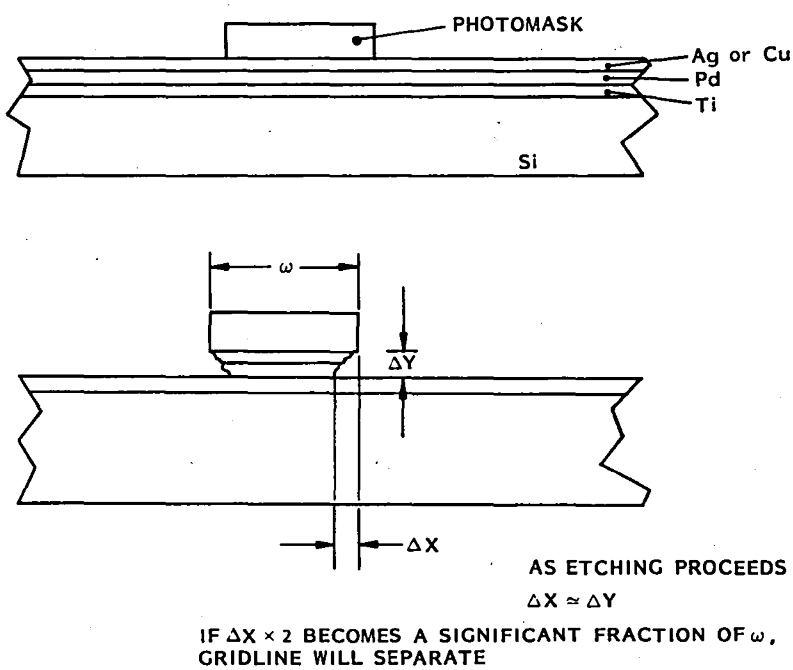


Figure 2-5 Reverse Etching Procedure

Acceptable cells were finally achieved by adjusting the time and temperature of the sintering process to give fair adhesion without appreciable electrical degradation. For copper to become an acceptable material for space solar power use, alternative processing will require development.

Additional information, observations and conclusions were addressed by Peter Iles, Chief Scientist for Applied Solar Energy Corporation (ASEC), during the latter phase in an attempt to understand the problems. His notations are included as Appendix A.

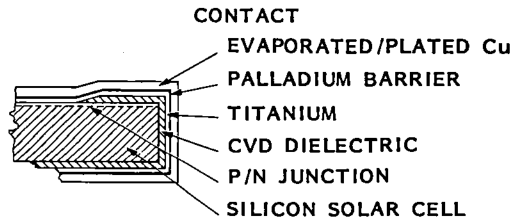
A summary of the specified cell features is shown in Table 2-1.

TABLE 2-1
SOLAR CELL PURCHASE SUMMARY

CELL VENDOR: APPLIED SOLAR ENERGY CORPORATION (ASEC)

	BASIC	GRIDDED BACKSIDE CONTACT	COPPER CONTACT
• SIZE (cm)	5.9 x 5.9	5.9 x 5.9	5.9 x 5.9
• CONTACT CONFIGURATION	WA	WA	WA
• BASE RESISTIVITY	2	2	2
• BSR	YES	NO	NO
• BSF	NO	NO*	NO
• WELDABLE	YES	YES	YES
• METALLIZATION		BORON	
EVAPORATION	Aℓ Ti Pd Ag	Ti Pd Ag	Ti Pd Cu
PLATE UP	Ag	Ag	Cu

*MINOR BORON DIFFUSION TO REDUCE BACK-SURFACE COLLECTION RESISTANCE



2.2 SIMPLIFIED SPECIFICATION

An LMSC basic cell specification, LMSC-D715825, was simplified and used for purchasing cells of each of the three cell types under consideration:

- Baseline AlTiPdAg contacts
- Low α Gridded Back Contact TiPdAg
- Low cost metallization TiPdCu

Table 2-2 lists a summary of the requirements mentioned in the basic specification. A modification of the metallization description was agreed upon with the cell vendor, Applied Solar Energy Corporation (ASEC), as well as the requirements and minimum process controls necessary to guarantee a repeatable solar cell for delivery. Several requirements such as contact thickness and surface smoothness are specifically essential to Lockheed in controlling the quality of the welding of the cell to the substrate.

TABLE 2-2
SIMPLIFIED SOLAR CELL SPECIFICATION

REQUIREMENT OF BASIC SPECIFICATION LMSC-D715825

- TYPE: N-P, WELDABLE/SOLDERABLE DIELECTRIC WRAPAROUND CONTACT
- DOCUMENTATION: GOVERNMENT COVERING: BAGGING MATERIALS, PACKAGING, I.D., SOLDERING, SAMPLING, STANDARDS, HUMIDITY CONTROL
- CONTACTS: EVAPORATED/PLATED AND SINTERED
- BACK-SURFACE REFLECTOR
- CONTACT TENSILE STRENGTH AT 45° PULL ANGLE: 350 gm FOR WELDABLE CELLS AND 600 gm FOR SOLDERABLE CELLS
- CHIPS: MAXIMUM EDGE CHIPS 0.13 cm, DEPTH 0.75; CORNER CHIPS NOT ALLOWED IN RADIUS REGION
- ANTIREFLECTIVE COATING: MULTILAYER
- CONTACT SMOOTHNESS: 200 nm RMS OR LESS
- CONTACT THICKNESS: 6 TO 9μ
- CONTACT DEFECTS: NONE IN AREAS OF ELECTRICAL BOND
- CELL DEFECTS: FREE OF CRACKS, SCRATCHES, LOOSENESS OR PEELING GRIDS, INCLUSIONS, AND RESIDUES
- CRYSTAL ORIENTATION: 1·0·0
- CHEMICALLY POLISHED OR ETCHED TO REMOVE WORK DAMAGE
- PERFORMANCE: DEFINED
- OPTICAL PROPERTIES: $\alpha_s / \epsilon_N \leq 0.90$
- RADIATION DEGRADATION: <10% AT 2×10^{14} e/cm^2
- THERMAL CYCLING: WITHOUT DEGRADATION AFTER 1000 CYCLES FROM +55°C TO -190°C.
- DIMENSION/WEIGHT: DEFINED

ACCEPTANCE TESTS

- EACH CELL INSPECTED FOR DEFECTS AND DIMENSION
- CONTACT PULL STRENGTH TEST
- OPTICAL PROPERTIES: 10 CELLS FROM PRODUCTION
- TAPE TEST: TAPE PEEL FROM BOTH CONTACTS AFTER BOILING WATER--10 CELLS
- TEMPERATURE CYCLE: 1000 CYCLES AND CONTACT PULL STRENGTH IN EXCESS OF 70 gm (20 CELLS)
- CONTACT SMOOTHNESS: 5 CELLS

THIS SPECIFICATION HAS BEEN NEGOTIATED WITH ASEC.

- ADDITION TO THIS SPECIFICATION FOR THE CURRENT CONTRACT

2.3 ELECTRICAL PERFORMANCE

Five (5) cells of each type were selected for electrical performance measurements. Key performance parameters for each cell are listed in Table 2-3 with a typical I-V curve for each shown in Figure 2-6. The rather lackluster performance shown on all cells has been attributed to the cell assembly equipment available at the time of manufacture.

TABLE 2-3
ELECTRICAL PERFORMANCE SUMMARY

CELL		V_{oc}	I_{sc}	V_{mp}	I_{mp}	P_{mp}
Baseline Ag Plated						
STD	1	587.4	1302.3	487.5	1175.9	573.2
	2	589.1	1283.1	488.9	1162.9	568.6
	3	587.8	1293.6	482.0	1166.0	562.0
	4	593.0	1341.4	468.5	1185.7	555.5
	5	592.2	1311.1	467.8	1183.6	553.8
$\frac{1}{N}\sum_1^N$		589.9	1306.3	478.9	1174.8	562.6
Gridded Contact						
GC	1	575.6	1301.5	489.3	1096.5	536.5
	2	576.6	1279.5	455.5	1040.9	474.1
	3	582.1	1312.1	477.3	1096.2	523.2
	4	585.2	1306.6	479.1	1123.8	538.4
	5	569.0	1272.4	460.8	1080.2	497.8
		577.5	1294.4	472.4	1087.5	514.0
Copper Contacts						
CC	1	573.0	1248.6	458.4	1073.1	491.9
	2	577.9	1234.5	468.1	1051.0	492.0
	6	582.8	1242.0	454.6	1089.1	495.1
	7	581.1	1246.9	476.5	1094.5	521.5
	10	581.4	1251.1	476.7	1075.9	512.9
		579.2	1244.6	466.9	1076.7	502.7

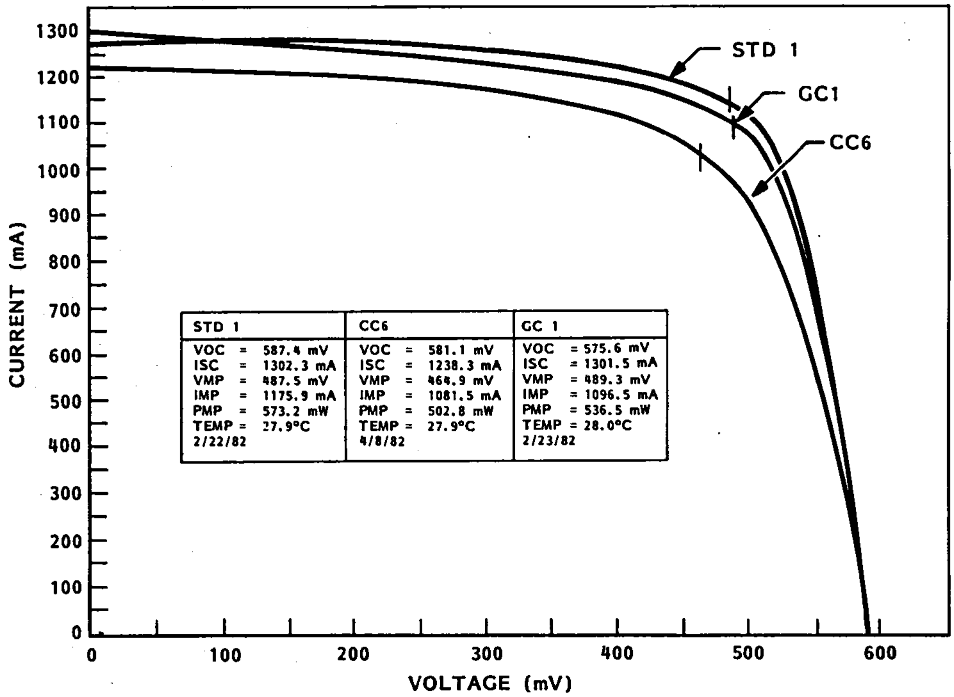


Figure 2-6 Electrical Performance Comparison Curves

2.4 THERMO-OPTICAL PERFORMANCE

Spectral reflectance and transmittance measurements were made upon a sample of each cell type received. The continuous TiPdAg back contact cell reflectance is shown in Figure 2-7. Key features to note are:

- The UV reflectance peak at ~.33 μ which is due to the cover filter
- The absorption region from 0.4 to 1.0 μ
- The high reflectance due to the aluminum BSR for $\lambda > 1.1$

The copper contacted cell, Figure 2-8, shows differences in regions 1 and 3. The UV reflectance peak noted at .33 μ on the Ag plated cell is reduced in intensity and split into two peaks. This same change is noted in the gridded contact cell. Since the UV reflectance is a function of the cover filter, it is apparent that the covers were damaged or a substitution made before installation. This supposition is supported by an examination of the reflectance curve supplied by the vendor (see Figure 2-9) with the covers showing a pronounced .3 μ reflectance peak. The effect of this low value in region 1 is a slightly higher absorptance value.

The copper contacted cell also shows a slightly higher reflectance in region 3 which may or may not be significant.

Significant differences between the gridded-back contact cell (Figure 2-10) and the continuous contact cell include the previously discussed UV reflectance peak in region 1 and high transmittance in region 3. An even higher value of transmittance would be expected with the addition of an AR coating on the back surface.

Integrated solar absorptance for each cell type is shown in Table 2-4. For the copper and gridded cells, the listed value will be slightly higher than expected due to the low UV reflectance from the cover.

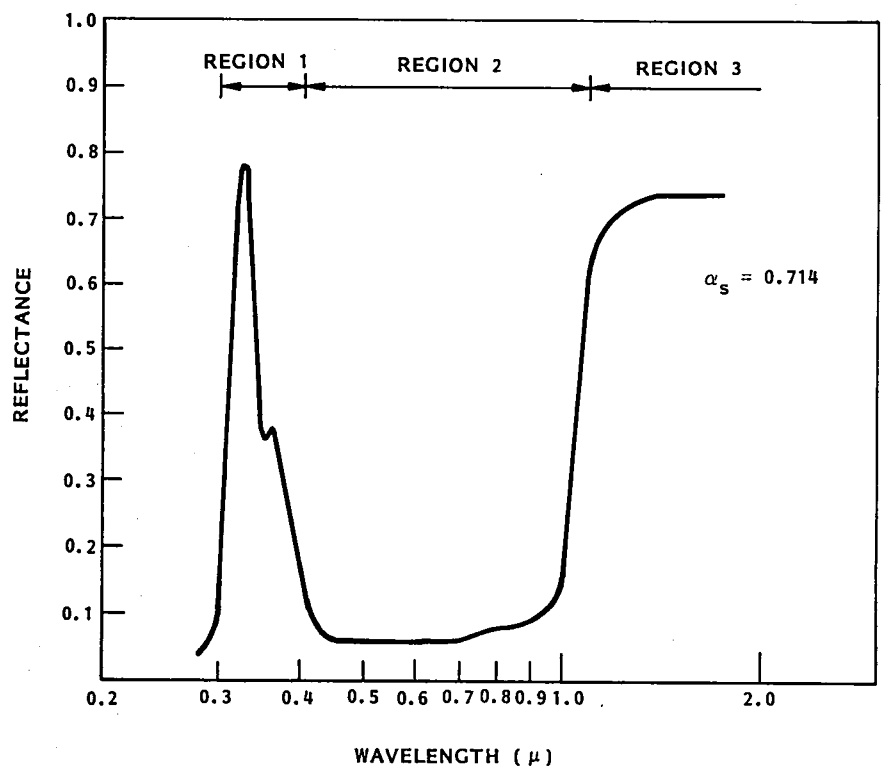


Figure 2-7 5.9 x 5.9 cm Silver Contacted Solar Cell Spectral Reflectance

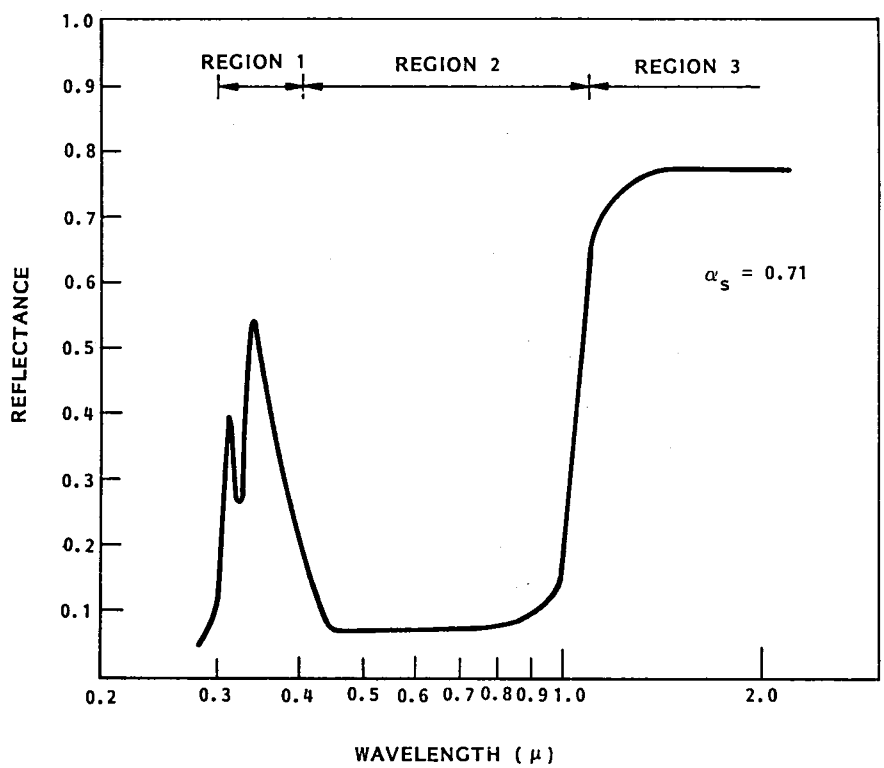


Figure 2-8 5.9 x 5.9 cm Copper Contacted Solar Cell Spectral Reflectance

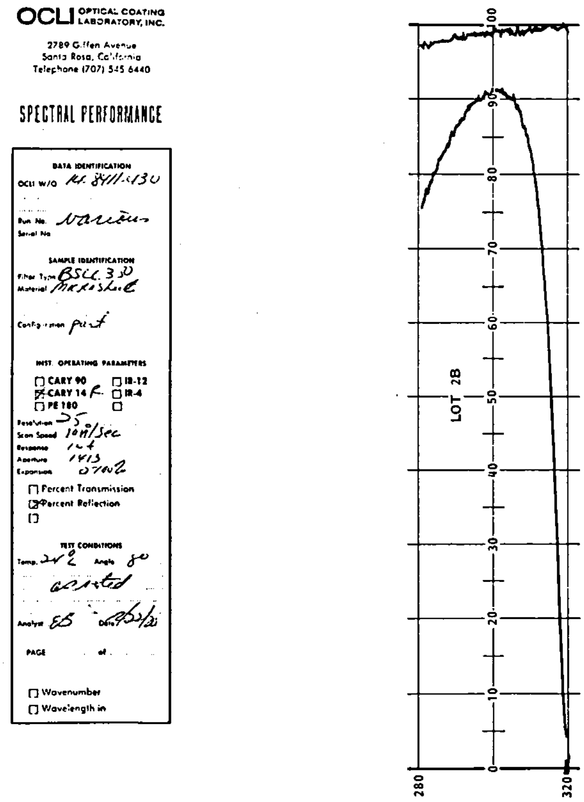


Figure 2-9 Reflectance Curve - OCLI

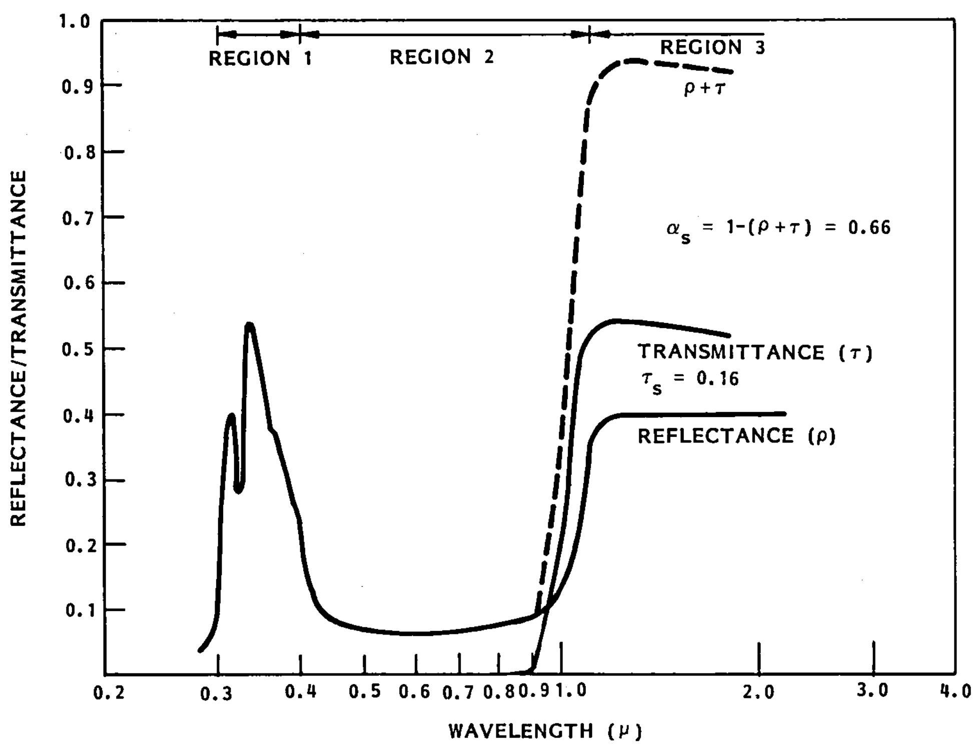


Figure 2-10 Gridded Back Contact Cell Reflectance and Transmittance

TABLE 2-4

SOLAR ABSORPTANCE/EMITTANCE

CELL DESCRIPTION	α_S	ϵ
Baseline BSR Cell with Ag Contact	0.714	0.82
Copper Contacts	0.71	0.82
Gridded Back Contact	0.66	0.82

2.5 PULL TESTING

Two (2) each of the gridded back and copper contacted cells were selected for pull testing. Figures 2-11 and 2-12 show a typical cell mounted in the pull test fixture and the details of the test tab attachment. Data from these tests is shown in Table 2-5.

Test data shown for the baseline cell is a compilation of the test results obtained at LMSC during an evaluation of cells and welding techniques. As such, it represents a statistically significant number of cells and the optimum achievable weld/ metallization strength.

Data on the gridded back contact was surprisingly low. The metallization procedure used is identical to the conventional process and as such should have yielded higher pull strengths than were achieved. The low N-contact pull strengths are consistent with the failures experienced during thermal cycle testing and are a result of poor adhesion between the metal and the dielectric layer. This type of failure is blamed on the use of an older lab vacuum coater.

A more surprising result was the excellent adhesion achieved on the copper contacted cells. As previously discussed, severe problems were encountered in attempting to sinter the copper onto the cell to achieve good adhesion without degrading the electrical performance. The final process was a compromise with a low temperature sinter. In order to prevent further diffusion, the interconnects and pull tabs were soldered rather than welded. The high pull strength value may be due in part to the solder area being perhaps 100X larger than the weld area, thus the pull values shown are for a larger contact area and should be higher.

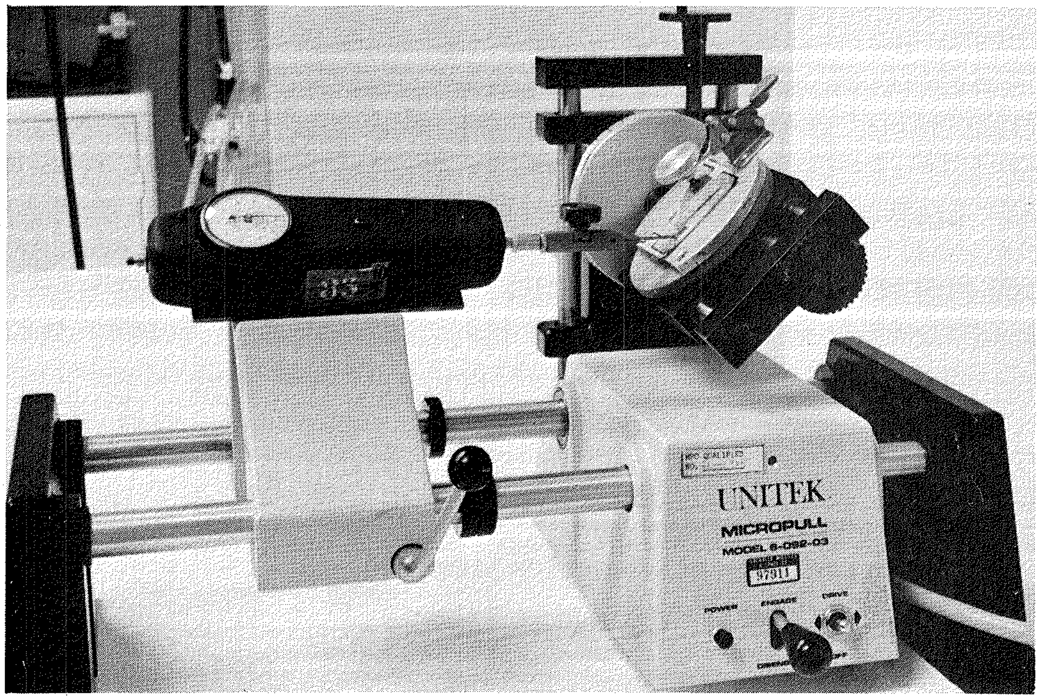


Figure 2-11 Pull Tester

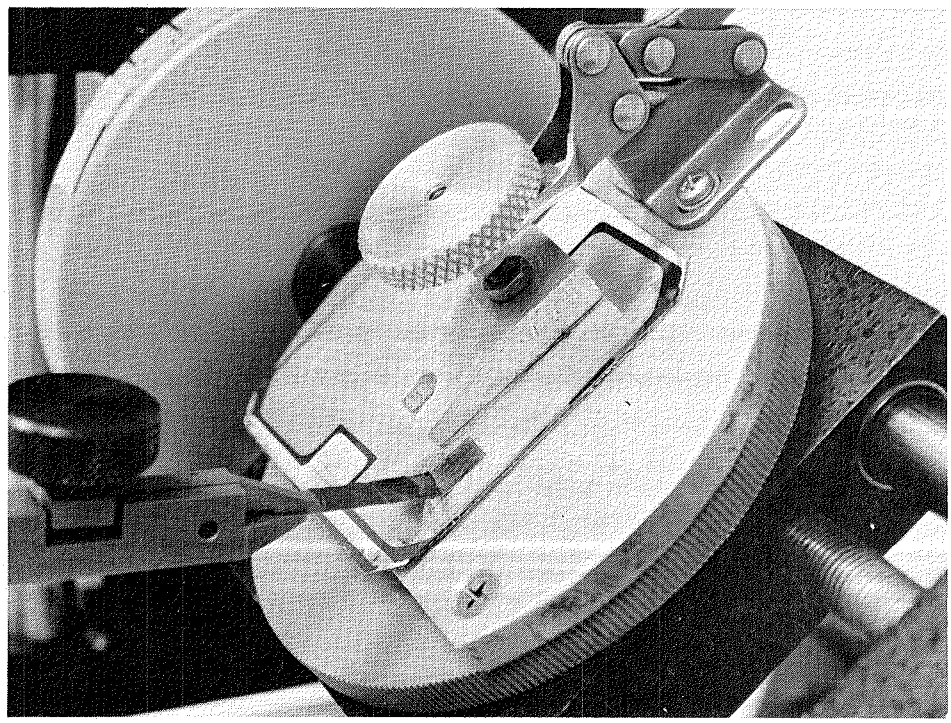


Figure 2-12 Pull Test Sample

TABLE 2-5
CONTACT PULL STRENGTH COMPARISON

CELL DESCRIPTION	N CONTACT PULL STRENGTH INDIVIDUAL	N CONTACT PULL STRENGTH AVG	N CONTACT PULL STRENGTH FAILURE MODE	P CONTACT PULL STRENGTH INDIVIDUAL	P CONTACT PULL STRENGTH AVG	P CONTACT PULL STRENGTH FAILURE MODE	COMMENTS
(1) BASELINE 5.9 cm WA CELL CONTINUOUS BACK CONTACT Ti-Pd-Ag	1.45						DATA FROM LMSC ID WELD DEVELOPMENT PROGRAM
	1.69	1.57					
(2) GRIDDED Ti-Pd-Ag BACK CONTACT 5.9 WA CELL	0.35		MF	2.35		CT	PULL STRENGTH IN LB/WELD JOINT
	0.22		MF	2.25		CT	
	0.35		MF	2.10		CT	
	0.07		MF	2.30		CT	
		0.25			2.25		
	2.0		CB	2.10		CB	
	1.5		MF	2.00		CB	
		1.75		2.20		CT	
					2.10		
(3) COPPER CONTACT 5.9 cm WA Ti-Pd-Cu	4.5		CT	4.0		CT	PULL STRENGTH IN LB/SOLDER JOINT
	1.1		MF	4.0		CT	
	3.0		CT	4.3		CT	
	1.0		MF	4.5		CT	
		2.40			4.2		
	4.25		CT	4.25		CT	
	3.50		CB	4.00		CT	
	3.8		CB	4.30		CT	
	2.0		CB	4.30		CT	
		2.9			4.2		

NOTE: MF = METALLIZATION FAILURE
CT = COPPER PULL TAB FAILURE
CB = CELL BROKE

WELD SCHEDULE

WELD VOLTAGE = 0.63V
IR SETTING = 4.07
ELECTRODE FORCE = 2.0 LB
ELECTRODE GAP = 0.012 IN.

2.6 SUPERSTRATE ADHESIVE EVALUATION

Selection of an adhesive for superstrate application proved difficult when conditions typical to space bonding of covers to cell were required. The ideal adhesive that makes the superstrate so attractive is a sheet adhesive that wets without a primer and has limited flow after a melt temperature of approximately 300°F. This feature was adequately met by Sheldalh GT 100 hot melt polyester resin. However, when optical and orbital conditions were considered, this material proved to be inadequate, even though its demonstration of the superstrate concept was considered excellent. Other conditions which must be met are: 1) UV stability, 2) optically clear (high solar transmittance), 3) low outgassing, 4) charged particle resistance, 5) temperature range compliance -180°C to +100°C, and 6) low thermal expansion coefficient comparable to silicon. Recognizing that polyester resins would darken to some degree in ultraviolet irradiation, alternate adhesive systems were surveyed. It was not Lockheed's intention during this contract to develop an adhesive that would meet all conditions, but rather to determine whether an off-the-shelf material existed that could be used to replace GT 100 for all superstrate layups. The survey indicated that no sheet material was available and that all hot melts such as Ethylene-Vinyl-Acetate (EVA), polyamide, epoxy or polyester would require a UV additive compounded in the resin formation. General classes of clear thermoplastics which are available in thin film form are listed in Table 2-6 showing relative comparisons. It is obvious that additional work would be required to optimize all physical and operational conditions. However, vendor discussion has led LMSC to believe that a sheet adhesive could be formulated to meet our needs. Lockheed chose to continue using GT 100 adhesive for superstrate module fabrication and rapid thermal cycling tests. Test results are discussed in Section 3.

Ultraviolet testing, sponsored by another program, was made available by simply providing samples of superstrate adhesive and glass cloth to their set of candidate materials for lamination between two 6 mil sheets of 0211 microsheet.

TABLE 2-6

CLEAR THERMOPLASTIC FILM MATERIALS

POLYMER BASE	THERMAL EXPANSION COEFFICIENT (in./in.°F X 10^{-6})	MAXIMUM SERVICE TEMPERATURE (°F)	MODULUS OF ELASTICITY (psi X 10^{6})	LIGHT TRANSMITTANCE PERCENT	ULTRAVIOLET RESISTANCE
SILICONE	50	500		90	EXCELLENT
FEP	105	400	0.07	82-85	GOOD
POLYCARBONATE	38	250	0.5	92	GOOD
POLYARYLATE	40	300	3	75	GOOD
GLASS	0.35	600	17	93	EXCELLENT

Fifteen (15) sample laminates were fabricated using 5.9 x 5.9 coating and bare 6 mil 0211 microsheet covers laminated into 10 adhesive combinations with or without scrim cloth. For test results and sample descriptions, see Table 2-7.

TABLE 2-7

ULTRAVIOLET IRRADIATION TEST - RESULTS OF VARYING LAMINATED COVERGLASS ADHESIVES

SAMPLE	GLASS BASE	ADHESIVE	GLASS CLOTH	COVER GLASS	PRETEST τ_s	POSTTEST τ_s	$\Delta\tau_s$
1	0211	-0-	-0-	-0-	0.916	0.909	0.007
2	0211	GT100	-0-	0211	0.879	0.598	0.281
3	0211	GT100	3 mil PVA GLASS	0211	0.873	0.478	0.395
4A	0211	93-500	-0-	0211	0.899	0.899	0.000
4B	0211	93-500	-0-	0211	0.899	0.898	0.001
5A	0211	93-500	7-mil PVA GLASS	0211	0.882	0.867	0.015
5B	0211	93-500	7 mil PVA GLASS	0211	0.886	0.858	0.028
5C	0211	93-500	7-mil PVA GLASS	0211	0.827	0.800	0.027
6	0211 (AR-UV)	93-500	6-mil ACRYLIC GLASS	0211 (AR-UV)	0.873	0.853	0.020
7	0211 (AR-UV)	93-500	7-mil PVA GLASS	0211 (AR-UV)	0.875	0.859	0.016
8	0211 (AR-UV)	93-500	-0-	0211 (AR-UV)	0.890	0.892	(0.002)
9A	0211	93-500	6-mil ACRYLIC GLASS	0211	0.879	0.808	0.071
9B	0211	93-500	6-mil ACRYLIC GLASS	0211	0.842	0.759	0.083
10A	0211	93-500	1.2 POLYESTER	0211	0.857	0.612	0.245
10B	0211	93-500	1.2 POLYESTER	0211	0.866	0.591	0.275

Each sample was illuminated by an X-25 Sun Simulator for 1318 equivalent sun hours at 5 sun intensity (AM0). Sample 1 provided the reference base for 0211 glass alone. Sample 3 represented the superstrate configuration and degraded severely as suspected. When GT 100 was replaced by wet DC 93-500, acceptable losses resulted. The PVA glass scrim cloth contributed less than 1% to the degradation while the remainder was due to the sheet adhesive, GT 100. The remaining samples are for comparison only.

Multi-100 kW

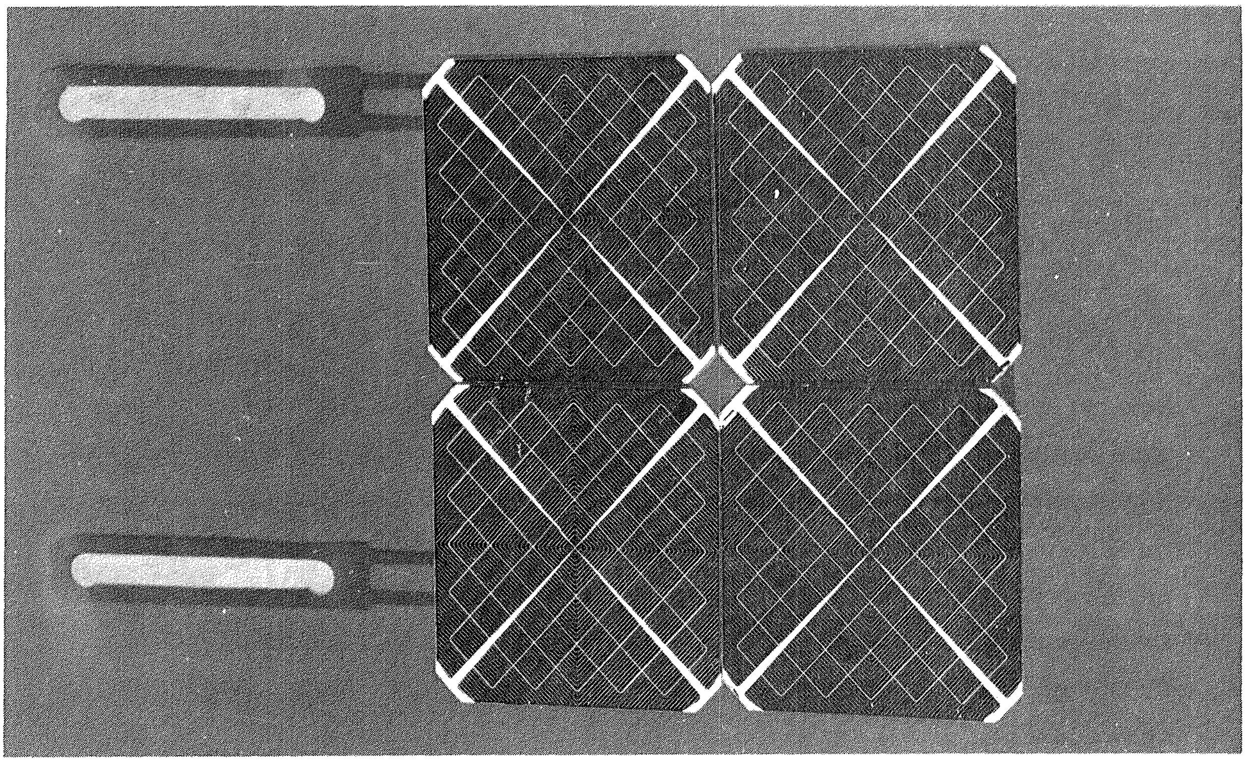
Planar Low Cost Solar Array Development

Final Report

3.0 TASK 2. MODULE FABRICATION TEST RESULTS

3.1 SMALL TEST MODULE DESIGN AND FABRICATION

Several 4-cell modules of each cell type were designed and fabricated for use in accelerated thermal cycle testing. The basic design used for the modules was developed during the last phase of the contract for the concept demonstration modules. Substrates were fabricated using the existing artwork. Two (2) versions of test modules were produced for each cell type: 1) conventional, incorporating individually-glassed cells, and 2) superstrate, utilizing either 0.006" or 0.009" thick 0211 microsheet as a cover. An example of each is shown in Figures 3-1 and 3-2.



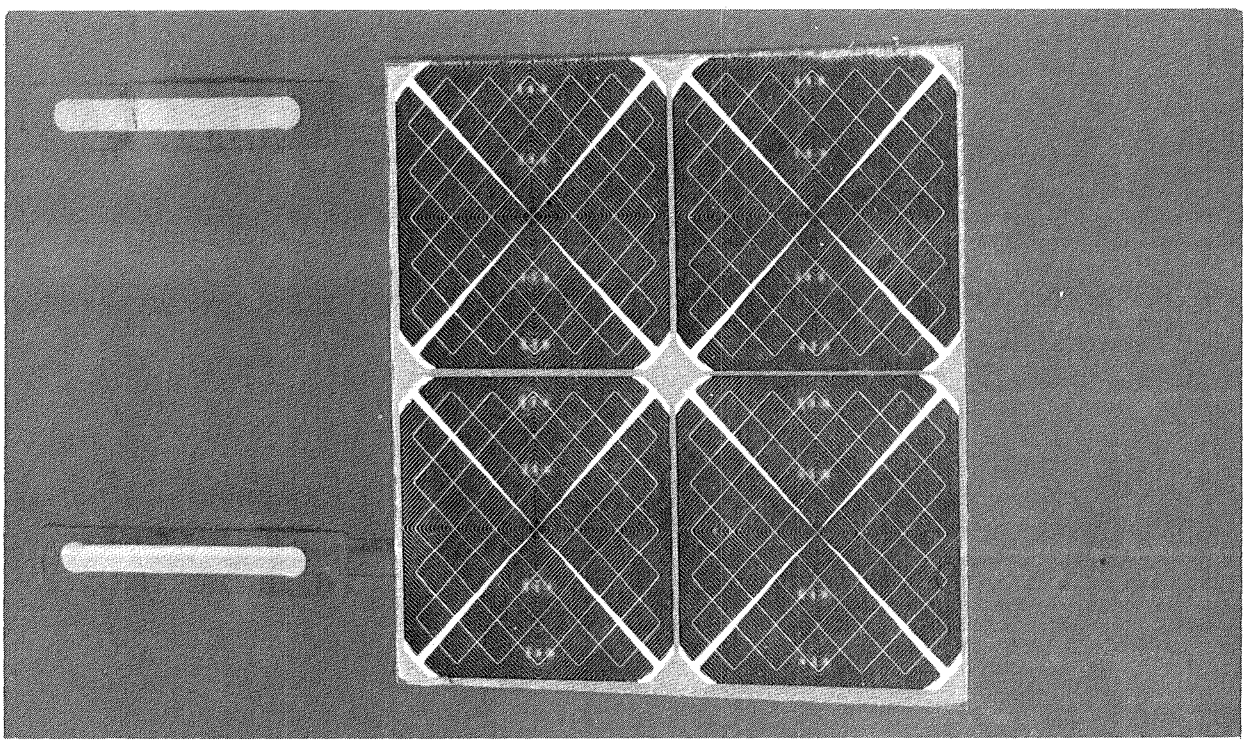


Figure 3-2 Typical 4-Cell Superstrate Module

3.2 THERMAL CYCLE TEST

The thermal cycle test facility is shown in Figure 3-3. The equipment shown allows temperature cycling controlled to a given profile with cycle times typically less than 10 minutes per cycle.

Test modules of each cell type and configuration were cycled between +71°C and -87°C for 1000 cycles. Temperatures were controlled and monitored on T/C's attached to representative cells with the same thermo-optical properties located in close proximity to the modules. Figure 3-4 shows the relative location of the modules in the chamber tray during testing.

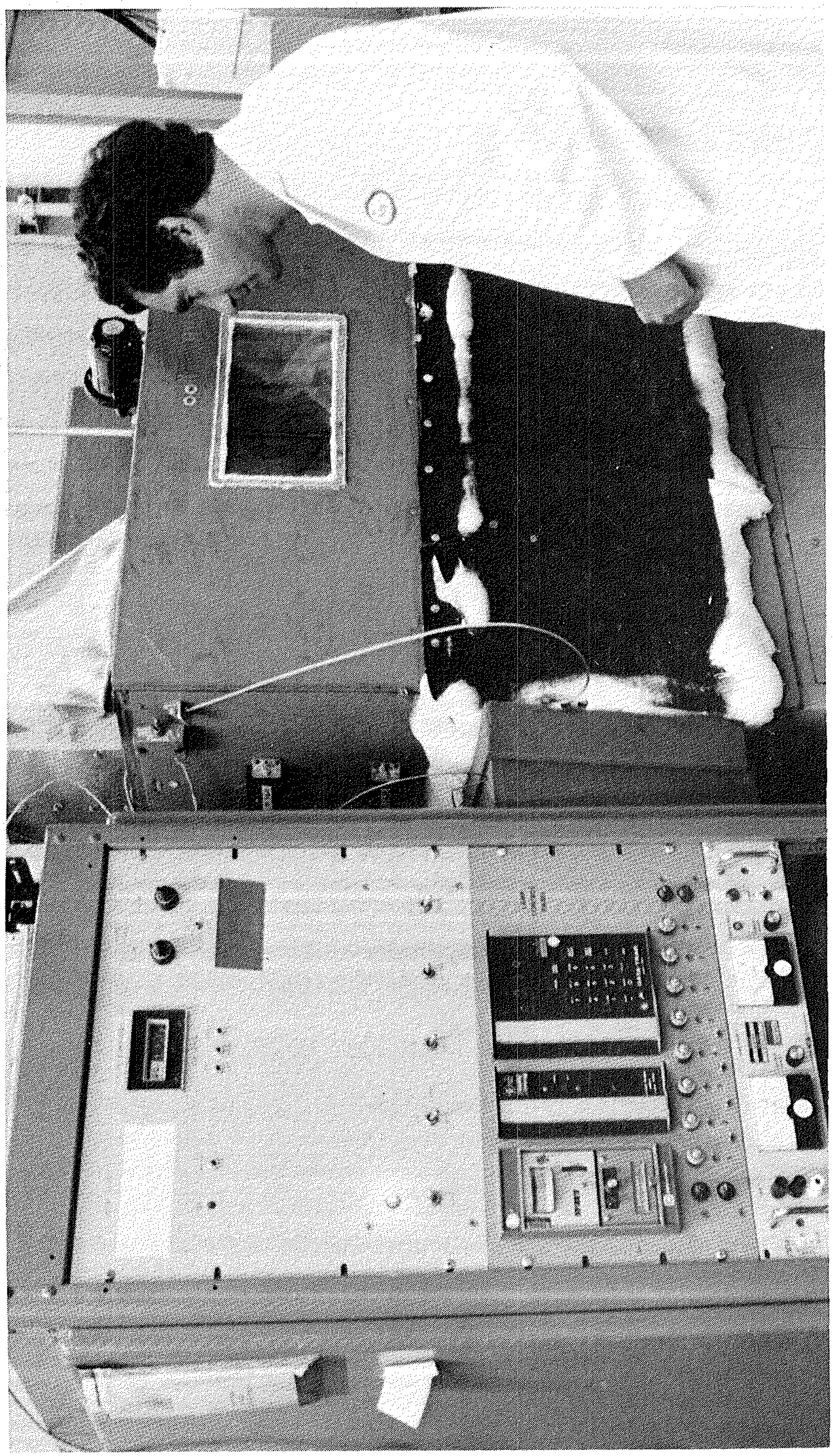
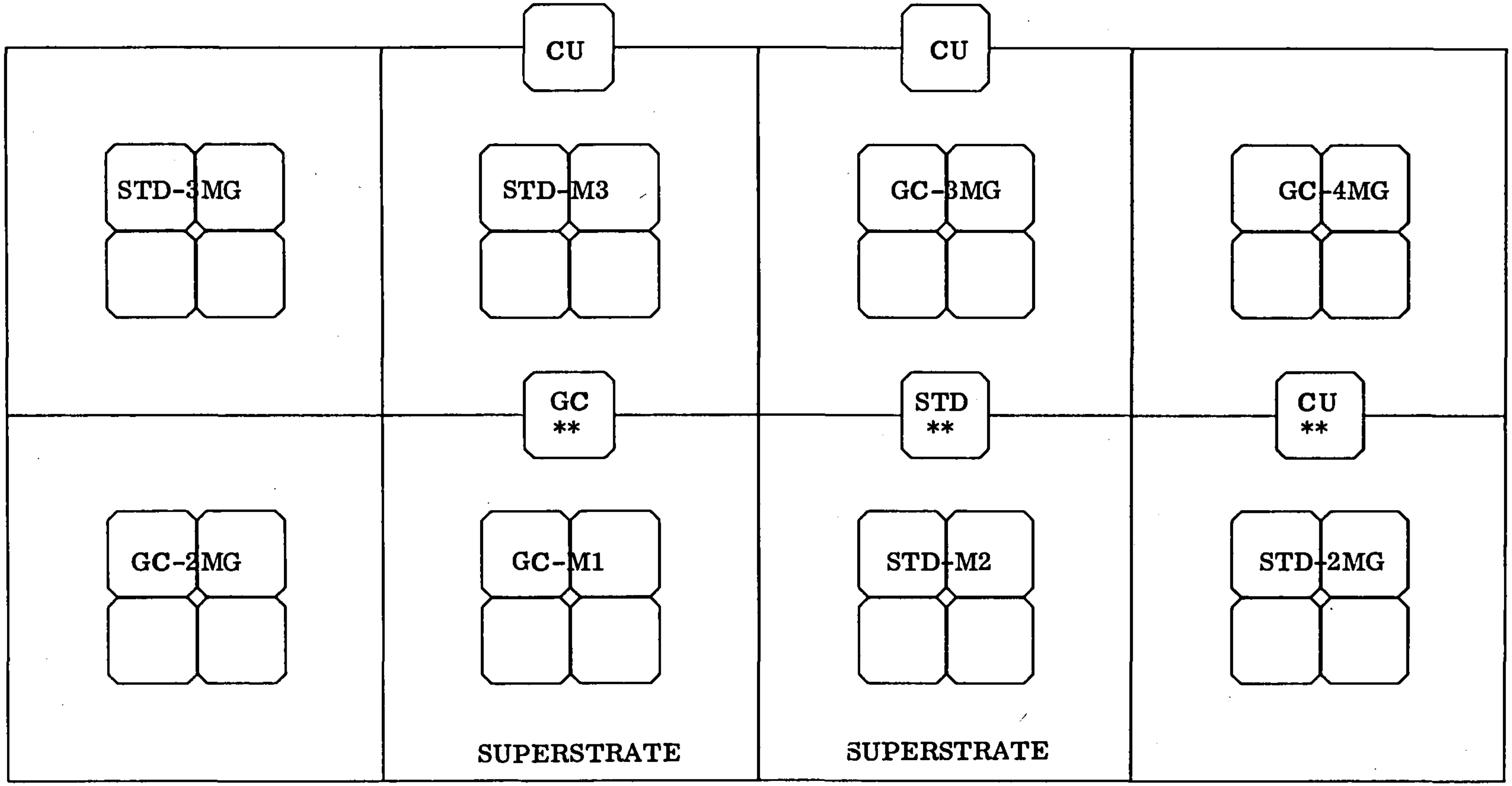


Figure 3-3 Quick-Look Thermal Cycle Chamber



* TC Locations

Figure 3-4 Quick-Look Box: Sample Location

3.3 ELECTRICAL PERFORMANCE

Complete electrical performance measurements were made on each module, both before and after the thermal cycle test. An X-25 solar simulator was used as the illumination source. Due to the presence of the substrate, effective cooling of the modules was inconvenient; therefore, the modules were allowed to equilibrate to approximately 60°C for testing. This higher than normal test temperature caused no difficulty in interpreting the results since relative changes in output pre- and post-test are the data sought.

A summary of the electrical test results are shown in Table 3-1.

TABLE 3-1

TEST MODULE ELECTRICAL PERFORMANCE SUMMARY

MODULE DESCRIPTION	VOC		IS/C		VMP		IMP		PMP			TEMP	
	INITIAL	POST T.C.	INITIAL	POST T.C.	INITIAL	POST T.C.	INITIAL	POST T.C.	INITIAL	POST T.C.	PERCENT Δ/CHANGE	INITIAL	FINAL
STD - M1	2101.1		1241.2		1638.8		1140.3		1868.8			60.5	
M2	2121.8	1697.3	1278.1	1267.4	1676.2	1442.7	1127.4	1183.3	1889.8	1715.0	-9.2	59.9	59.1
M3	2115.4	2088.8	1271.2	1263.5	1671.2	1650.1	1115.8	1117.3	1864.7	1843.5	-1.0	59.9	60.1
3MG	2035.2	2075.4	1319.4	1307.0	1587.5	1618.8	1161.5	1161.5	1843.8	1880.2	+2.0	60.0	60.2
2MG	2156.6	2137.9	1295.2	1200.1	1660.6	1646.2	1155.2	1147.9	1918.4	1889.7	-1.5	59.9	59.9
CC - 1MG	2042.2		1305.7		1531.7		1041.8		1595.6			60.0	
2MG	2055.6	2082.6[b]	1289.7	1269.6[b]	1562.3	1478.7[b]	1042.1	1005.7[b]	1628.0	1487.1[b]	-8.7	60.2	59.8
3MG	2048.8	2089.3	1290.1	1280.7	1557.1	1504.3	1075.9	1058.5	1675.3	1592.2	-5.0	60.0	59.9
4MG	2030.0	O.C.[a]	1290.7	O.C.	1542.8	O.C.	1047.8	O.C.	1616.6	O.C.	-100.0	60.1	-0-
M-1	2023.8	2043.5[b]	1238.2	1232.7	1477.4	1410.0[b]	970.8	944.6	1434.2	1331.9[b]	-7.1	60.0	59.9
1D[c]	2047.5	2040.8	1218.3	1228.8	1535.6	1530.6	960.5	967.3	1474.9	1480.7		59.7	60.5
CC - 1	2066.8		1244.3		1488.1		1056.0		1571.4			60.2	
2	1562.1		1250.0		1124.7		1059.3		1191.4			60.0	

(a) O.C. = OPEN CIRCUITED
(b) CELL HELD IN CONTACT WITH COPPER TRACE FOR POST T.C. ELECTRICAL. NORMAL POST-TEST CONDITION WAS OPEN.
(c) DISPLAY MODULES

In general, thermal cycling was met without noticeable degradation on modules where standard baseline cells were used in substrate or superstrate configuration. Slight cracking occurred around the weld joints; see Appendix B for module inspection records. Although not desireable, this was typical to test results on similar weld joints on test modules cycled in excess of 25,000 cycles. The solution may be to use slitting to relieve the copper between the weld joints or use only one weld per pad. The purpose would be to relieve the stress between adjacent joints as expansion and contraction occurred during temperature cycling.

The 4 modules using the gridded back contact cell all failed in open. All N-contact welds, 6 per cell, failed at the metal interface with the SiO dielectric. These modules were pressed by hand back into contact, for electrical testing purposes only, to determine if cell degradation occurred. The values shown in Table 3-1 exist for this reason. No related silicon degradation was established. This type of failure is consistent with metallization processing rather than thermal cycling.

The copper contact cells were not thermal cycled for the purpose of verifying weld and metallization integrity since the "N" pad copper was already missing on many of the cells, indicating poor adhesion. However, 3 copper cells were mounted in the chamber with 1 being used as a temperature monitor. Only the monitor cell had been soldered, but neither it nor the 2 bare Cu cells were affected by the thermal cycle. This was not unexpected, since the contact to cell stressing is minimal as a single cell.

3.4 LARGE MODULE DESIGN AND FABRICATION

As a continuation of the superstrate work initiated during the previous contract phase and as a replacement for an oral mid-term, three large superstrate modules were fabricated. One module, designated the "development unit" was fabricated with glass simulators in place of cells; the second module, designated the "engineering unit," utilized mechanical cells from each of the 3 cell designs considered; while the third module, which is being delivered, used only gridded back contact cells. All 3 modules are of similar design and were fabricated using the same process. The covering material is a sheet of Corning 0211 microsheet approximately 16" x 14.5". The 16" dimension is defined by the die size utilized to pull the glass and includes two stiffening beads along the edges. As received, the edges perpendicular to the beaded sides are a wavey, free-form cut which were scribed and broken to the final 14.5" size. Layup of the modules proceeded using the procedure developed during the last contract with layers of Craneglass 230 non-woven scrim cloth and Sheldahl GT-100 polyester adhesive between the cover material and the cells or simulators. After proper positioning is achieved, the whole assembly is vacuum bagged and cured at 350°F and approximately 20 lb of pressure. In order to continue the evolution of the superstrate design for space applications, two modules incorporated stiffeners installed during the initial layup. Installation of stiffeners during the layup process was intended to improve the handling characteristics of the completed panel, increase the stiffness of each module and prevent the propagation of cracks which initiated at an edge defect. Two different materials were tried. The development unit utilized existing unidirectional graphite stiffeners approximately 0.25" wide by 0.031" thick. As a result of thermal expansion effects discussed later, the engineering unit utilized S-glass fibers layed directly in the polyester. No stiffening was incorporated into the deliverable module.

All modules show encouraging results but were less than a total success. The developmental unit, shown in Figure 3-5, experienced some cracking due to a combination of edge defects and a mismatch in thermal expansion coefficients. Tracking was also encountered in the engineering unit. The deliverable module, Figure 3-6, was almost perfect with only two small cracks.

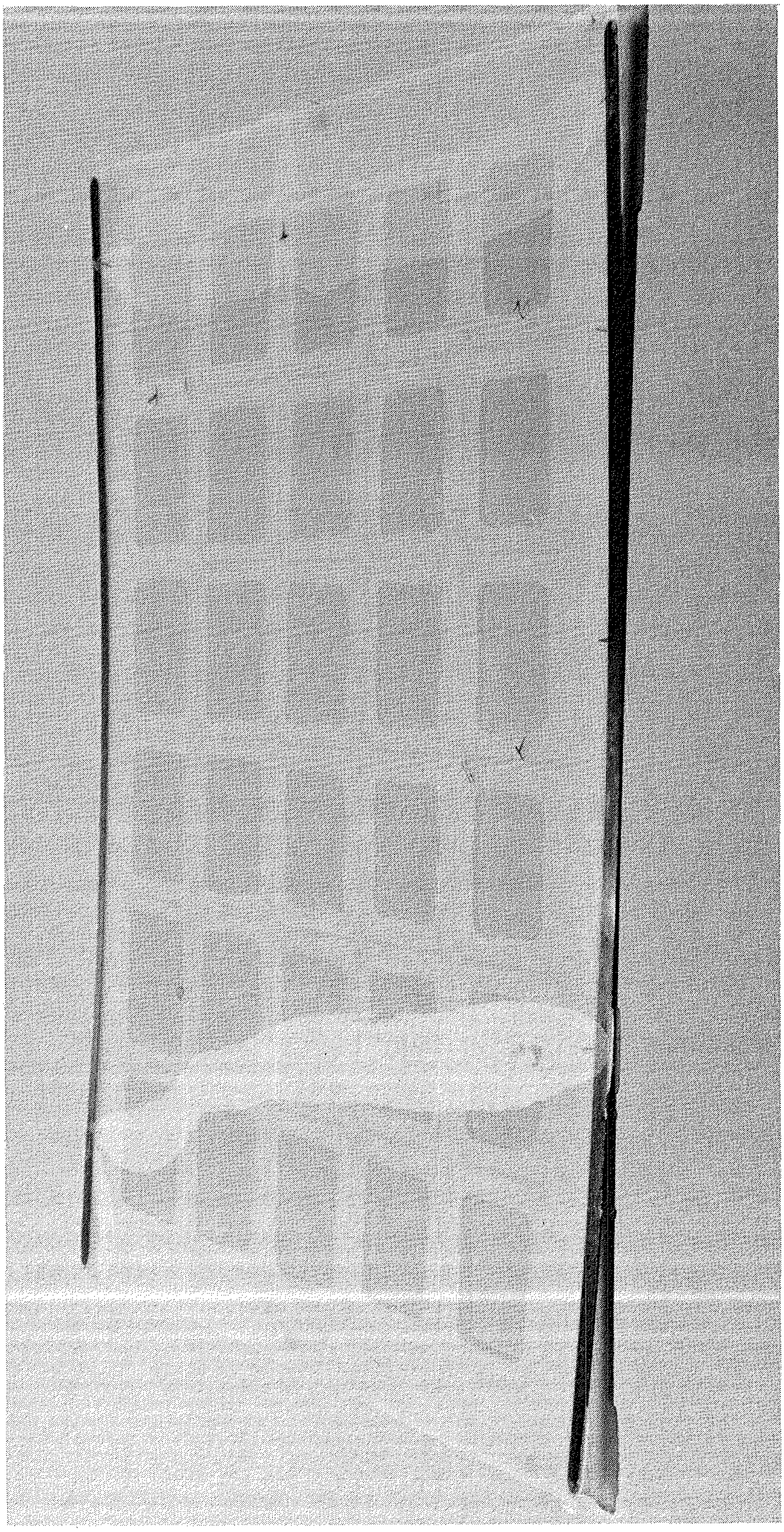


Figure 3-5 Completed Development Module

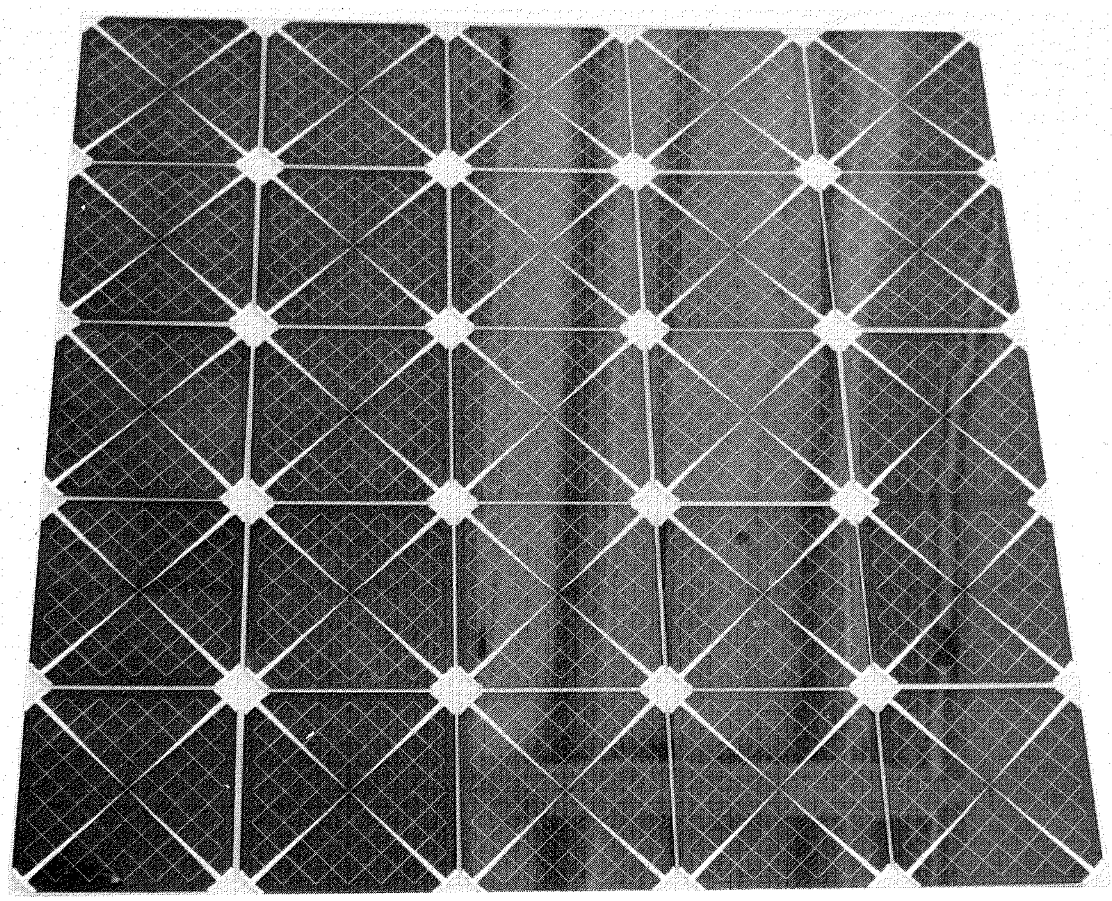
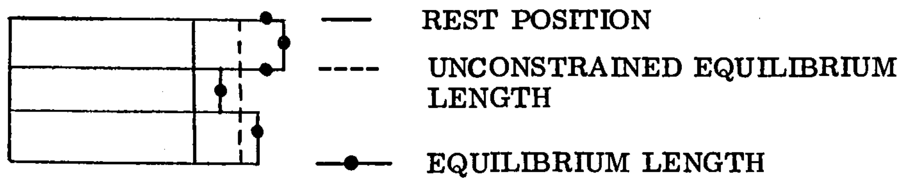


Figure 3-6 30-Cell Superstrate Module (14" x 16")

A conservative analytical model was constructed of the stiffener/adhesive/glass assembly in an effort to gain a quantitative insight into the nature of the cracking mechanism. Considered in the model was a system consisting of 3 rigid bars which could move relative to each other only through deformation. An equilibrium position is calculated for this material stack after a temperature excursion as a weighted average of the unconstrained equilibrium position of each layer. The weighting functions used are a function of the elastic modulus and the layer thickness. Residual stress in any layer is a result of differences in the unconstrained length and the stack equilibrium length. Figure 3-7 shows the thermal stress model diagrammatically and the necessary equations.



$$\text{Net} = \frac{\sum_{i=1}^{N} t_i \; E_i \; \alpha_i \; \Delta T}{\sum_{i=1}^{N} t_i \; E_i}$$

$$\sigma_i = (t_{met} - \alpha_i \, \Delta T) \; E_i$$

t_i = thickness of i th layer

E_i = Elastic Modulus

α_i = CTE

σ_i = Stress in i th layer

Figure 3-7 Thermal Stress Model

Since the model considers all 3 materials to be rigid bars, the calculated stresses should represent an upper bound if the central layer undergoes a significant shearing deformation. Material properties and the model results are shown in Table 3-2. The stress levels calculated are well below the levels required to cause failure in any of the bulk materials. This model emphasizes the necessity to achieve a defect-free edge.

TABLE 3-2
MATERIAL PROPERTIES AND MODEL RESULTS

MATERIAL	CTE	E	$\Delta L/L$	1 - Dim σ	
1. Graphite Fiber Direction	0	$\theta\ 10^6$	0	1, 2, 3 ~850	2, 3, 4
2. 0211	$4 \times 10^{-6}/°F$	11×10^6	8×10^{-4}	-1×10^4	1×10^4
3. Polyester/glass	$30 \times 10^{-6}/°F$	2×10^6	6×10^{-3}	~550	~250
4. S-glass	$2\text{-}4 \times 10^6/°F$	$\theta\ 10^6$	8×10^{-4}		~250

In an effort to find a low cost process to cut the glass and leave a fused defect-free edge, several vendors of laser machining services were contacted. Of these, Iowa Laser Technology had experience in trying to cut thin glass pieces. In discussions with the technical personnel at ILT, it was learned that they had experienced similar cracking as was found in LMSC's previous attempts at laser cutting. They had developed a technique which utilized the thermally induced fracturing to cut glass for another customer. After evaluating the results, their process did not appear to meet LMSC requirements.

Several possibilities exist in the area of laser machining of glass including high peak power density, short pulse and laser-reactive bas techniques, but these will require development for our application.

Multi-100 kW

Planar Low Cost Solar Array Development

Final Report

4.0 COST COMPARISON

Several low cost components, processes and design techniques were investigated during this task in an effort to quantitatively verify some of the previous analytical assumptions. A new metallization material was investigated and a modification to the cell to reduce α was implemented. Larger area, polycrystalline cells, were compared with the 5.9 cm baseline single crystal cell. The cost per watt of power generated using these alternatives will be discussed below.

Table 4-1 shows a cost comparison for each cell type and option considered. The first cell type listed is the baseline 5.9 x 5.9 cm, single crystal, plated silver wraparound contact cell. Taking advantage of a simplified specification with fewer inspection steps and cosmetic requirements as well as more efficient processing results in a lower limit of $85.69/watt.

Gridded back and copper cells are modifications of the baseline cell which were fabricated and tested during this contract. Gridding the back contact to improve the thermal performance of the cell appears very promising. The very simple contact design tested showed that viable large area cells with α's as low as 0.62 are definitely feasible. Figure 4-1 shows the analytically predicted temperature of the cell as a function of α. With the gridded cell an on-orbit temperature of 18°C with an efficiency of 13.4% is a realizable design goal. The reduction in operating temperature will have significant second order cost effects which will lead to substantially greater system cost savings than the 6% predicted or $79.94/watt.

Replacing silver with lower cost copper has not been fully verified. The production difficulties and the need for new process development will result in a higher cost than originally expected.

An estimated cost for copper contacted cells shows an identical cost to plated silver contacted cells of $85.69/watt; however, there still may be a significant cost advantage for copper contacts at the blanket assembly level.

TABLE 4-1

SOLAR CELL COST PROJECTIONS

		13.5 KW		135 KW		406 KW	
		$/cen	$/WATT	$/cen	$/WATT	$/cen	$/WATT
5.9 X 5.9	PLATED CONTACTS	70.00	119.97	50.00	85.69	50.00	85.69
5.9	GRIDDED AG CONTACTS	70.00	111.91	50.00	79.94	50.00	79.94
5.9	Cu CONTACTS	70.00	119.97	50.00	85.69	50.00	85.69
5 X 5	POLY- REG CONTACTS	7.75	22.93	7.05	20.95	6.75	19.97
	FEED THROUGH	9.70	28.70	8.80	26.04	8.45	25.00
10 X 10	POLY - REG CONTACTS	20.00	14.81	18.00	13.33	17.25	12.78
	FEED THROUGH	25.00	18.52	22.50	16.67	21.50	15.93

NOTE: 5.9 X 5.9 cm EFFICIENCY = 12.8 PERCENT
10 X 10 cm EFFICIENCY = 10.0 PERCENT
5.9 X 5.9 cm GRIDDED BACK ON-ORBIT EFFICIENCY = 13.4 PERCENT

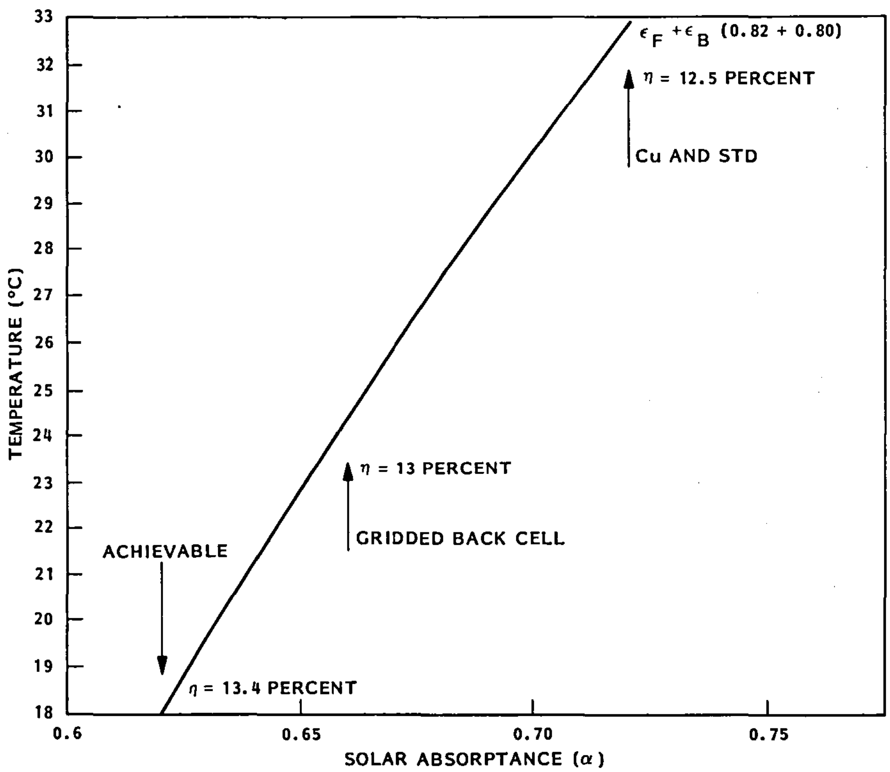


Figure 4-1 Predicted Thermal Performance Vs α

Recent advances in polycrystalline cell technology have resulted in lower cost cells with competitive power conversion efficiency. One of the largest producers of these cells is Solarex Corporation which was contacted for cost, performance and delivery information. Estimated costs of large area (5 x 5 cm and 10 x 10 cm) polycrystalline cells are shown in Figure 4-1. A conservative average AM0 efficiency of 10% was assumed for the power calculations.

Two cell sizes were considered, 5 x 5 cm and 10 x 10 cm, with both conventional contacts and with a proprietary "Feed through" contact which results in a coplanar back contact. At this time, radiation effects, solar absorptance and temperature coefficient are unknown parameters for these cells. The potential 80% reduction in cost to $15.93/watt makes polycrystalline cells an attractive candidate for Multi-100 kW arrays.

Multi-100 kW

Planar Low Cost Solar Array Development

Final Report

5.0 SUMMARY

This report documents the results of an on-going study to examine a means of developing Low Cost Multi-100 kW Planar Solar Arrays. This phase culminated in the fabrication of 8 4-cell and 3 30-cell (large area cell) superstrate modules using a baseline and 2 prospective lower cost solar cells, backside gridded and the copper contact cell. Eight (8) 4-cell substrate modules using all cell types were also fabricated as control units. Eight (8) of the 16 modules were thermal cycled through 1060 cycles from -73° to +87°C. Varying results occurred which directly related to poor contact adhesion of the gridded back and copper contact cells. The standard baseline cell was unaffected by the cycling. Modules made up of individually covered cells were compared to those made up in superstrate configuration. The individually covered cells were assembled with DC 93-500 wet adhesive, while the superstrate adhesive was dry sheet GT-100. Minor additional cracking occurred in the superstrate modules (stress relieving) while none occurred in the modules which used individual covers.

Modules of each configuration failed where the gridded back N-contact interfaced with the SiO dielectric. Thermal cycling only accelerated the failure, but as has been typical of past thermal cycling history, it would not have been the cause of failure if the metallization had been properly processed.

Cracks in the copper around the weld joints occurred in both the baseline and gridded backside contact cells, suggesting thermal stressing occurs between weld nugget and adjacent copper.

All modules where copper contact metallization was used were soldered to the Kapton-Copper substrate. The metallization was so poor that these modules were not subjected to thermal cycling. Copper cells were individually thermal cycled without metallization degradation.

Three (3) 30-cell superstrate modules were fabricated. The third module (deliverable) was made up of low output gridded back cells. Careful selection of glass, scrim, and adhesive demonstrated that superstrates of 14" x 16" size can successfully be assembled and welded.

The technology improvements necessary to achieve the cost savings projected during the last contract phase were demonstrated in the fabrication of actual prototype hardware. Gridding of the back contact when used with either a conventional substrate or a superstrate design will substantially reduce the cell operating temperature and thereby increase its on-orbit efficiency and cost effectiveness. Discussions with the vendor after this preliminary manufacturing trial resulted in a ROM cost estimate for gridded cells which was the same as for conventional contacts.

Copper contacted cells failed to meet all the goals of the project. Several terrestrial vendors are using Cu as their standard contacting material which demonstrates the technology. The ROM cost estimate received from the vendor, however, does not support the earlier projected cost savings. At this point, Cu is still questional for space use until adequate development can be accomplished.

Cost projections for the polycrystalline cells are very attractive. The performance of this type of cell in the LEO radiation environment is completely unknown at this time but definitely deserves some effort.

Multi-100 kW

Planar Low Cost Solar Array Development

Final Report

6.0 RECOMMENDED FOLLOW-ON TECHNOLOGY

Planar solar arrays will continue to maintain their ranking position for large area solar power until compact concentrators which will maintain their configurations in orbital environment and are reliably produced are available. Concentrator cells for which Gallium Arsenide is the chief contender are still several years from production and qualification. The subject of solar positioning with two axis control which is sufficiently sensitive to concentrator narrow off-angle requirements is known but has never been properly addressed. On the other hand, planar array systems are not nearly so sensitive to production precision or to orbital solar positioning as are concentrators. Also, several solar cell options are available in silicon which are directly adaptable to planar use.

Thus, a continuance in low cost planar array development is valuable in the sense that the basic technology does exist. The next major step should be to develop a firm set of requirements and design a system to meet these conditions. Immediate usefulness to component refinement should be devoted to furthering the superstrate concept toward becoming the basic support structure for the blanket, thus eliminating the Kapton copper substrate.

The elements of this study should be:

- Large Area Solar Cell
  - Single crystal
  - Polycrystal
  - Dendritic
  - HEM Process
- Coverglass Optimization
  - Material
  - Thickness
  - Coatings
  - Size

- Adhesive
  - Non-degrading
  - Compatible with LEO Thermal Excursions
  - Coefficient of Thermal Expansion Optimization with Silicon
  - High Transmissibility
- Interconnection (Wraparound or Conventional Cells)
  - Material
  - Configuration
  - Technique
  - Method
- Superstrate Processing As Affected by the Materials and Configuration Variance

The initial task would be to establish the availability and characteristics of each material. Where new materials are required, size limitations exist or techniques are missing or weak; manufacturers, suppliers and/or industry will be contacted for assistance. The microelectronic industry, for instance, uses welding and assembly techniques which could have possible application to the superstrate concept.

A decision tree approach would be used to arrive at the two or three most promising configurations. Analytical modelling would become an essential companion in arriving at configurations approved for production. Appropriate sized superstrate modules would be manufactured according to material used and the specific configuration.

The significant factor that threads its way through this entire study, design, and fabrication of hardware is the constant responsibility to minimize cost to the lowest possible figure in $/watt.

The final effort would be to establish and conduct a qualification program designed to evaluate all aspects of ascent and orbital requirements and compare the results to the derived analytical models.

A conclusive statement would be made associated with each configuration, the qualification status, and the projected cost to build Multi-100 kW size solar array blankets.

APPENDIX A

NOTES ON COPPER CONTACTS

(Taken from Letter to J. A. Mann from Peter Iles, Chief Scientist, Applied Solar Energy Corporation, dated 10 May 1982)

NOTES ON CU CONTACTS

1. Cu is cheaper than Ag, and is bondable by most methods.

2. Cu may have more severe tarnishing problems and may need protective overcoat.

3. Cu appears to form a non-ohmic barrier on Si, requiring use of additional interface metal.

4. Cu does not adhere well to Si, again requiring use of an interface metal, which may differ from that needed under #3.

5. Cells with predominantly Cu contacts (~3%) have shown good electrical performance if not heated.

6. Heating of Cu contact cells has caused serious loss of CFF. This has been traced to the penetration of Cu into the space charge region of the cells (near the front surface). Depending on the grid formation method, the critical temperature is as low as ~250°C or can be extended up to ~450°C.

7. Much work has been done to reduce the chance of penetration of Cu. These tests involve use of barrier layers (Pd, V, Mo, Cr, etc. or recently TiN), often with intermediate formation of a metal silicide which serves as a barrier.

   Present indications are that this shifts the problem to that of forming an impermeable barrier wherever Cu is applied to the front surface, a difficult task for cells with many fine grid lines.

   In addition, some failure has been attributed to penetration of Cu at the edge of the grid lines. This can be caused eg. by Cu electroplating, which forms a mushroom shape, leaving the Cu layer very close to unprotected Si surface. Some attempts have been made to make vertical side grid lines, either by complicated mask registration, or by applying the contact layer all over the cell surface, applying protective resist where grids are required, and etching back. These attempts have not been generally successful.

   With the TiN barrier which has shown recently good impermeability to Ag lines, deposited within the TiN layer (~5μ clearance each side of the lines), Cu has not shown comparable heating performance although the initial I-V curves were good, and the heat tests were high (~600°C). More tests are in progress to check the failure mode for Cu over TiN--surface migration is one possibility.

8. Cu can reduce the diffusion length (lifetime) of minority carriers in Si - however, levels about 10^{16} cm^{-3} are required, and these losses have not been the dominant ones in tests so far.

PRACTICAL PROBLEMS

For terrestrial uses, Cu has been applied by evaporation (TiPd Cu + Cu plating), by plating and by screened-on pastes.

The evaporated contacts (Westinghouse) were fairly good. Although as mentioned, could not always survive heating $\geq 300°C$. The pastes (B. Ross Associates) have shown adhesion problems, and loss in CFF when applied to the front surface.

The plated system was used at both Motorola and ASEC and gave fairly good results. Both methods used Pd as the underlayer and deposited Cu from electroless solutions. ASEC used Cu electroplating; Motorola originally used solder coating, later switching to Cu plating, with perhaps some solder coating.

The plating systems do not deposit well over insulating layers (as required in the present WA cells) and thus are not readily transferrable to such cells.

The evaporated system should be applicable to WA cells, either used in similar fashion to the TiPdAg contact system, or applied all over and grid patterned with back etch.

However, tests to date have not been promising. The rate of evaporation of Cu (even for thin layers 2-5 KA^o) is very slow so that the slice and mask are exposed to the E-gun source for long times (1/2 to 1 hour), and this appears to lead to delamination of the contacts from the $Si0_2$ or even to peeling of the $Si0_2$ itself.

Although the Cu electroplating bath used is relatively mild (~10% H_2 $S0_4$), there were signs of attack of previous $Si0_2$ layers on the bath contact, and thus suspicion that there was some interaction with the main insulating layer (which is critical for good WA cell operation).

CONCLUSIONS

Long term, Cu must be evaluated for low cost cell contacts. However, before its electrical and environmental quality can be assessed (especially in critical areas such as temperature cycling of welded bonds), a reliable method of application must be verified.

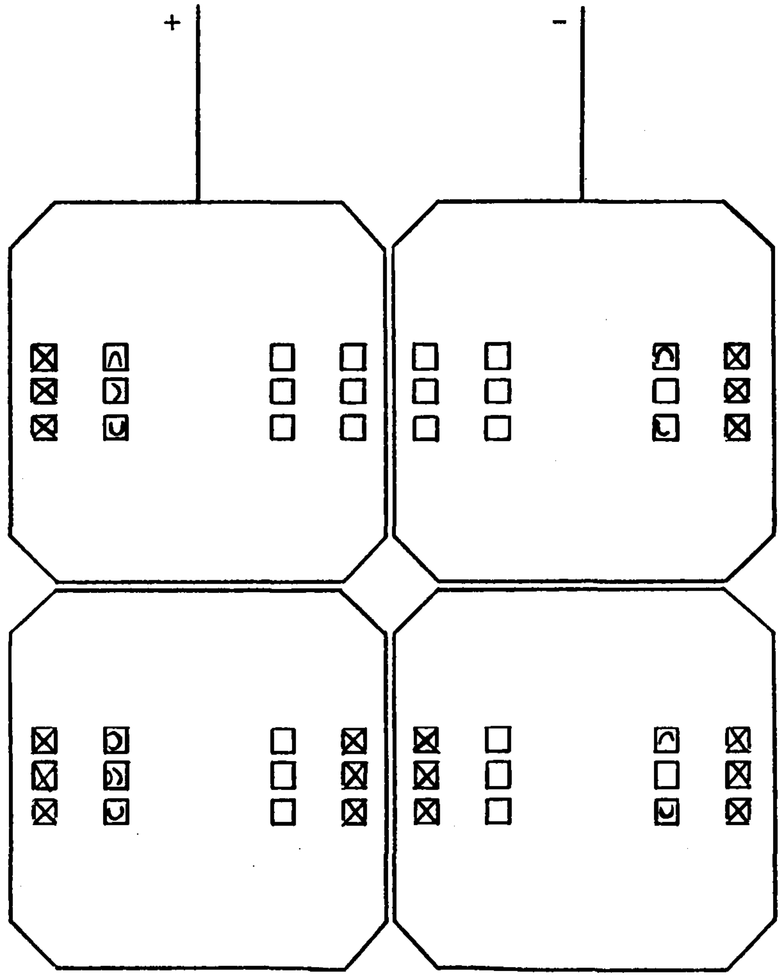
This suggests tests on simple cell structure (conventional contact configuration and less complex grid pattern). These simples can then be tested for their reliability when connected into arrays.

If the process solution needed to form space qualified Cu contacts is not unduly complex (or costly), then it would be worthwhile to extend the process to include the formation of WA contacts.

APPENDIX B

POST THERMAL CYCLE INSPECTION SHEETS

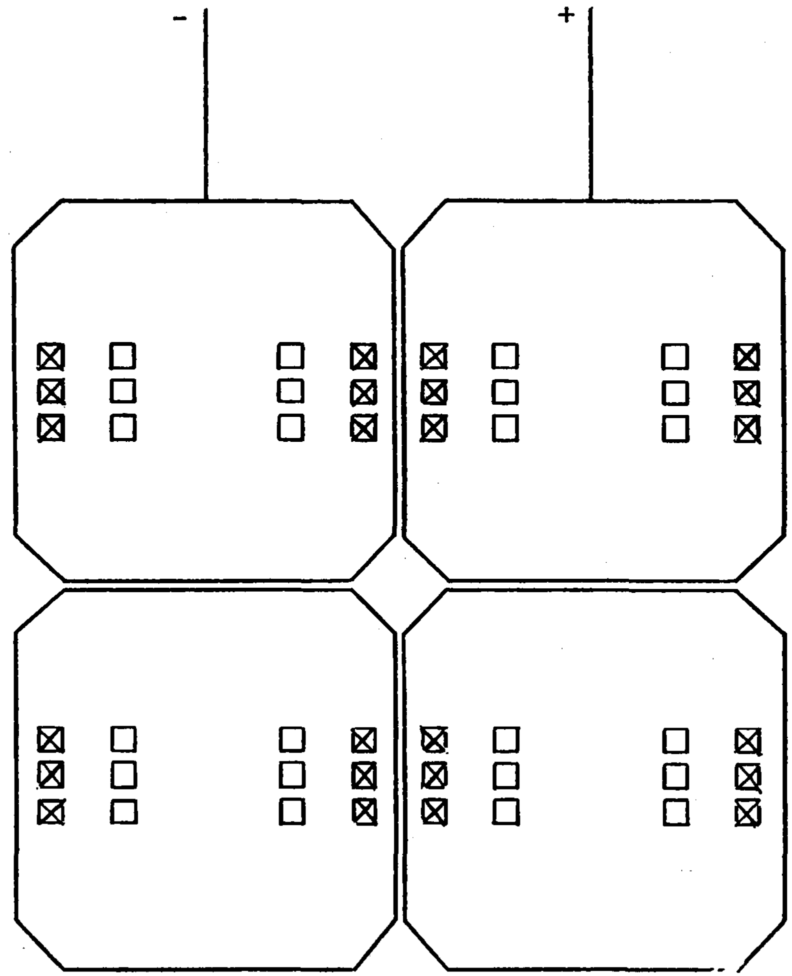
BACKSIDE



MODULE TYPE: GRIDDED

S/N: GC-M1

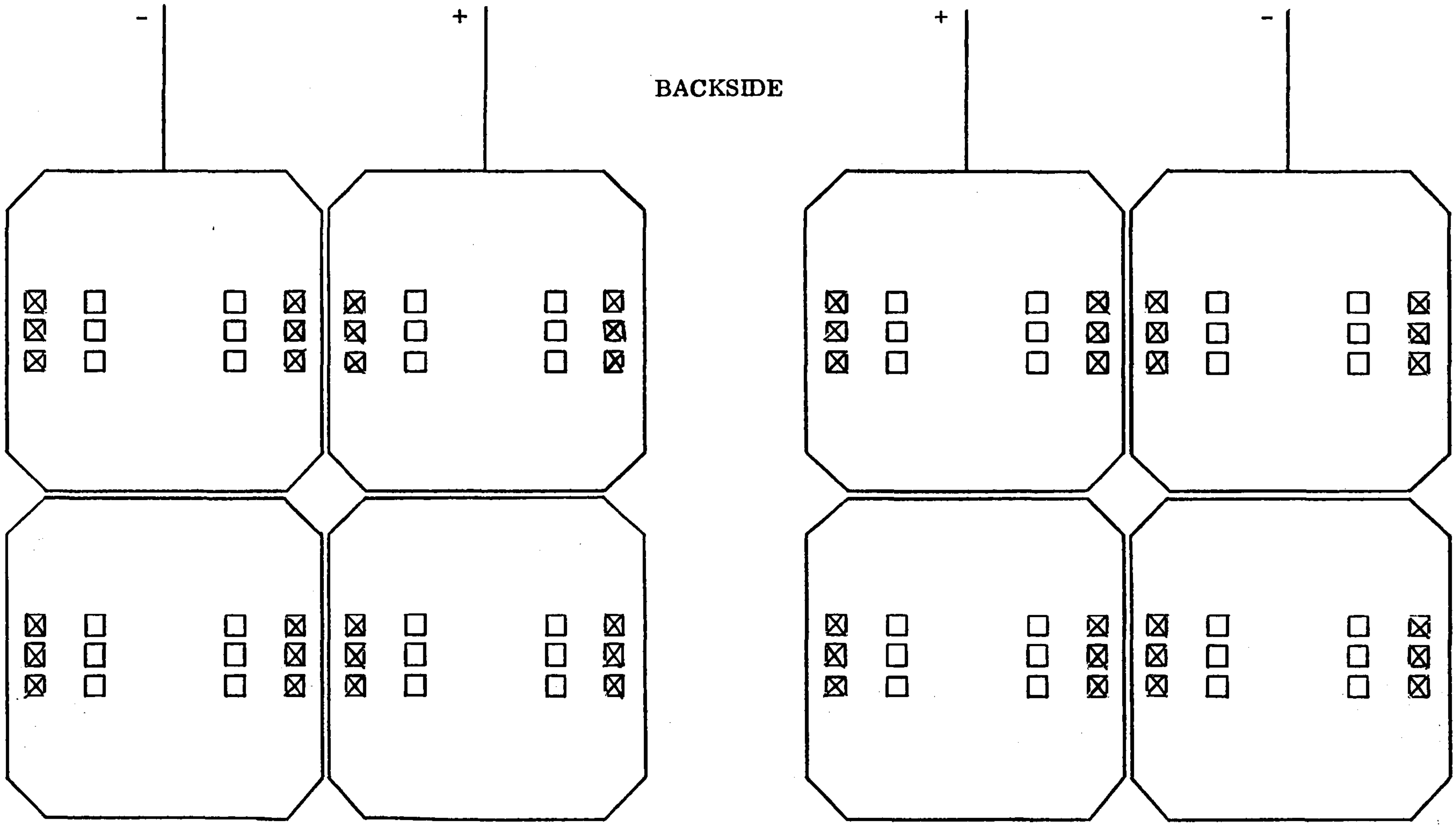
NOTE: X - Cell contact metallization failure
∩ - Weld fracture
Temperature Range: -73°C to +87°C
No. of Cycles: 1060



MODULE TYPE: GRIDDED

S/N: GC-4M6

POST RAPID CYCLE WELD JOINT INSPECTION SHEET



MODULE TYPE: GRIDDED

S/N: GC-2M6

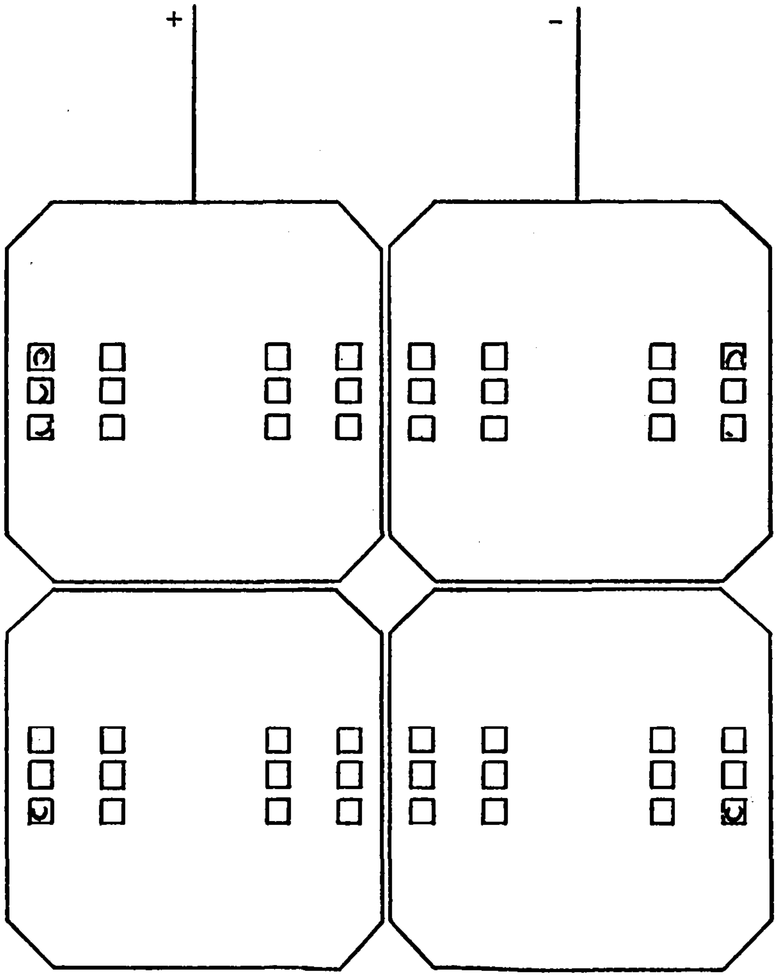
MODULE TYPE: GRIDDED

S/N: GC-3M6

NOTE: X - Cell contact metallization failure
∩ - Weld fracture
Temperature Range: -73°C to +87°C
No. of Cycles: 1060

POST RAPID CYCLE WELD JOINT INSPECTION SHEET

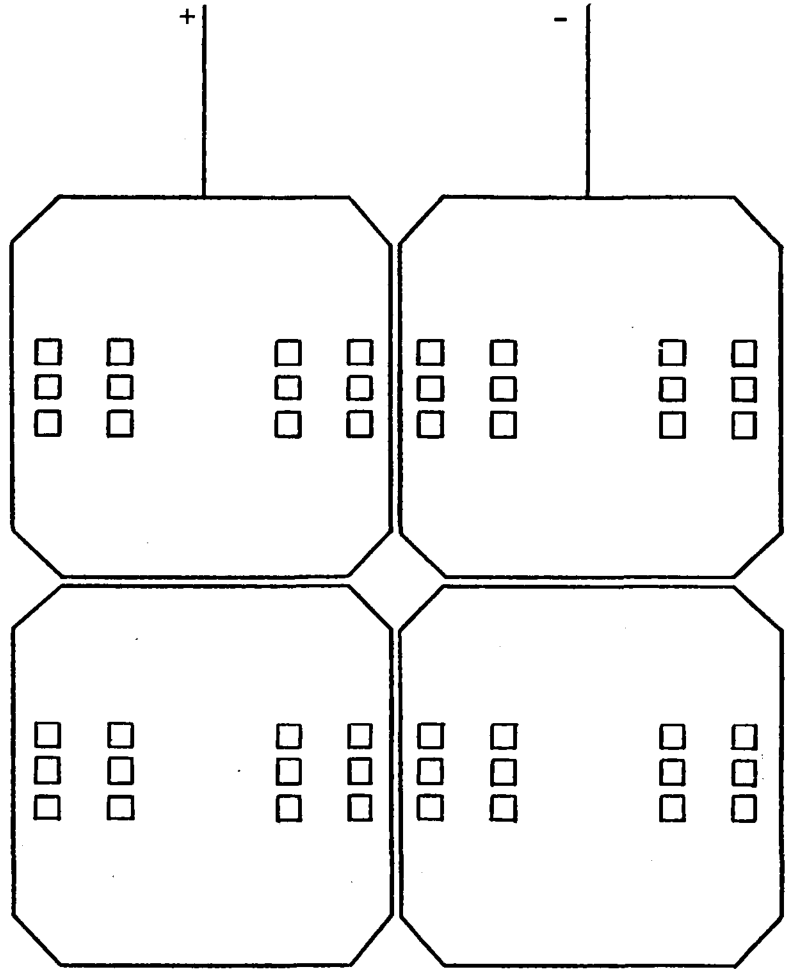
BACKSIDE



MODULE TYPE: STD CELLS

S/N: STD-M2

NOTE: X - Cell contact metallization failure
∩ - Weld fracture
Temperature range: −73°C to +87°C
No. of Cycles: 1060

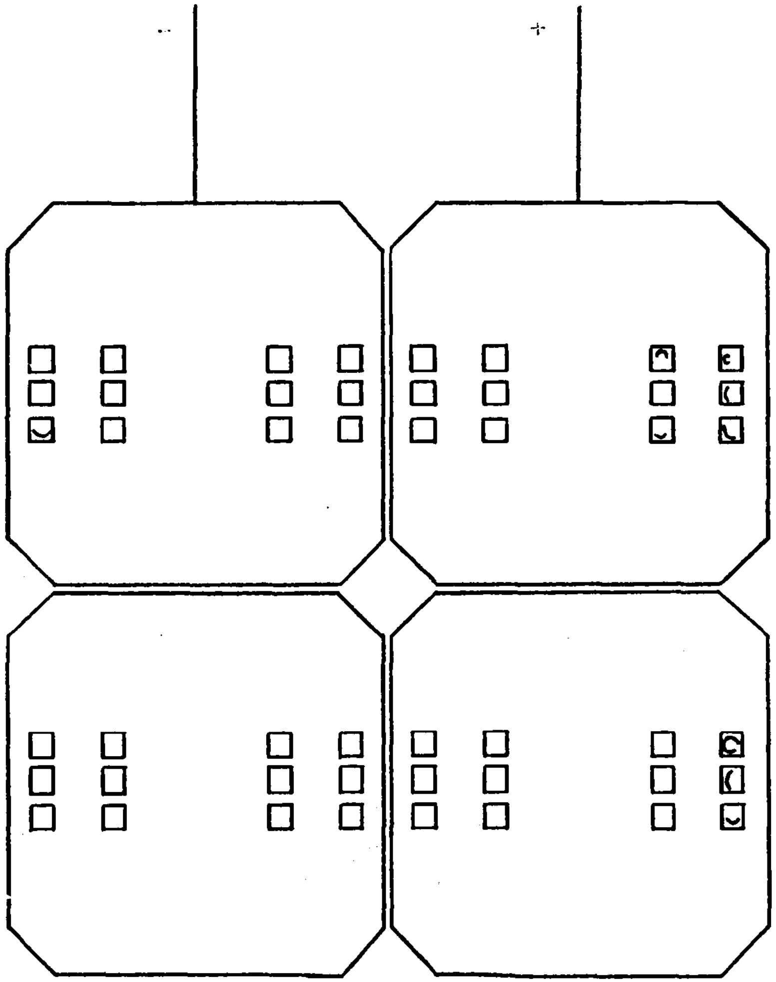


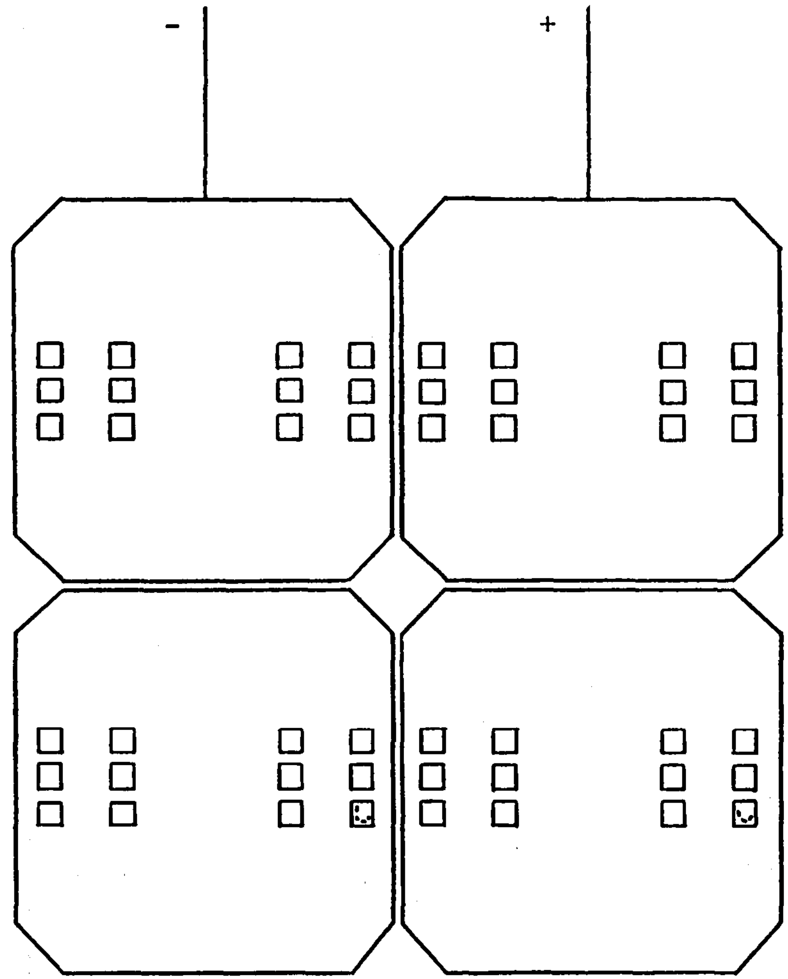
MODULE TYPE: __________

S/N: __________

POST RAPID CYCLE WELD JOINT INSPECTION SHEET

BACKSIDE





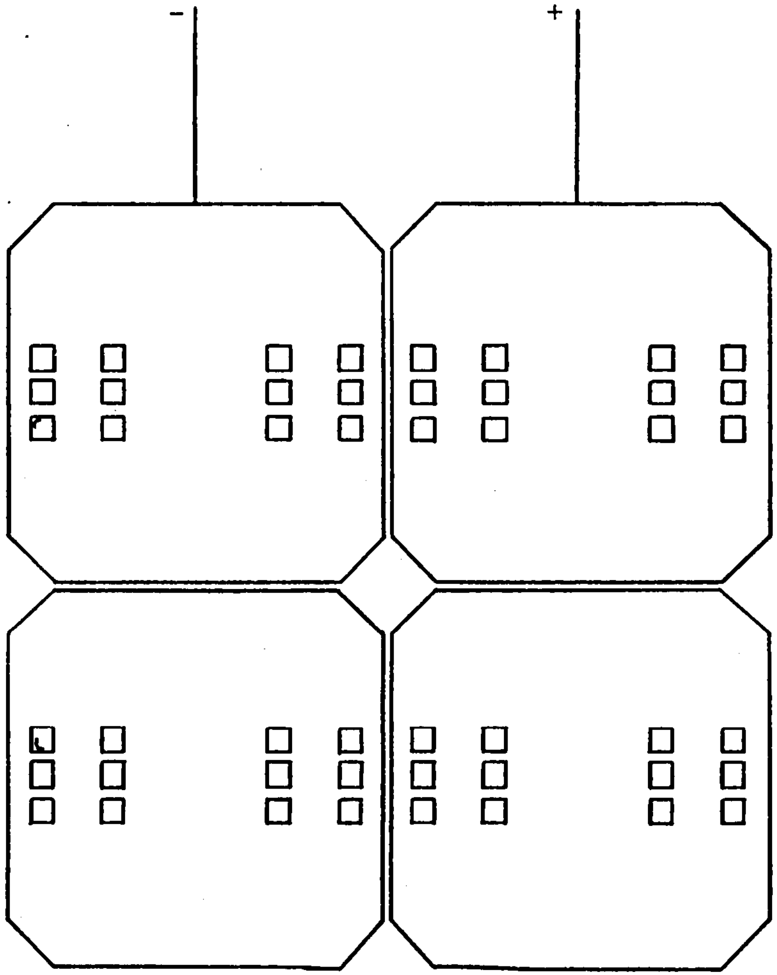
MODULE TYPE: STD CELLS
S/N: STD M3

NOTE: X - Cell contact metallization failure
∩ - Weld fracture
Temperature range: -73°C to +87°C
No. of Cycles: 1060

MODULE TYPE: STD CELLS
S/N: STD-2M6

POST RAPID CYCLE WELD JOINT INSPECTION SHEET

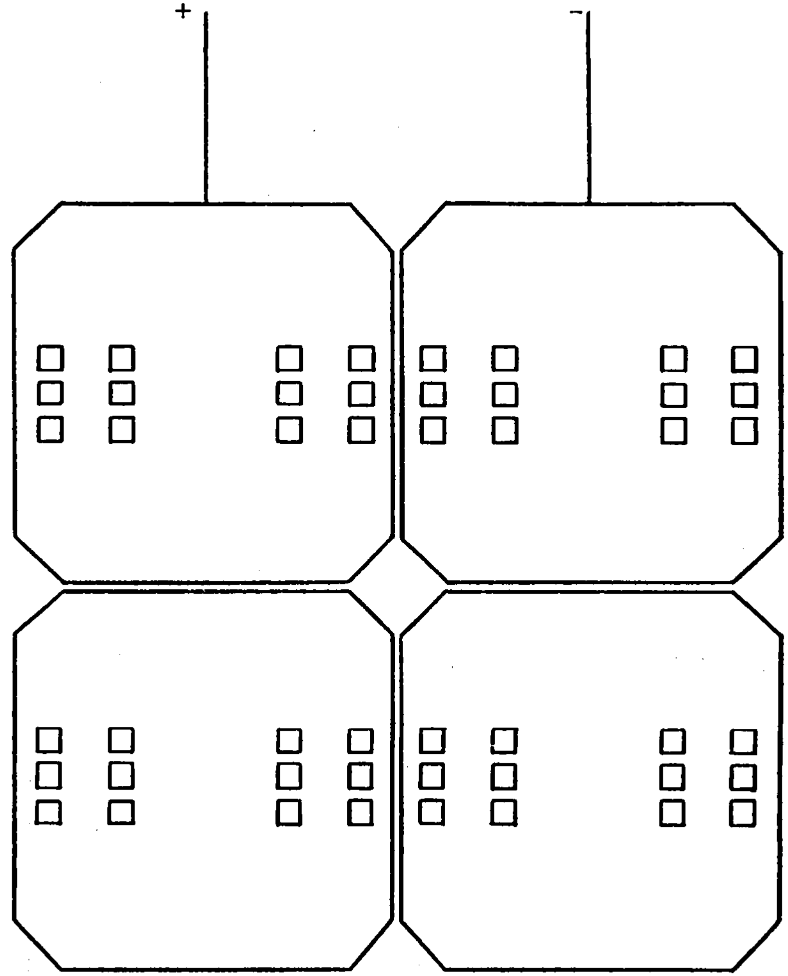
BACKSIDE



MODULE TYPE: STD CELLS

S/N: STD-3M6

NOTE: X - Cell contact metallization failure
∩ - Weld fracture
Temperature Range: -73°C to +87°C
No. of Cycles: 1060

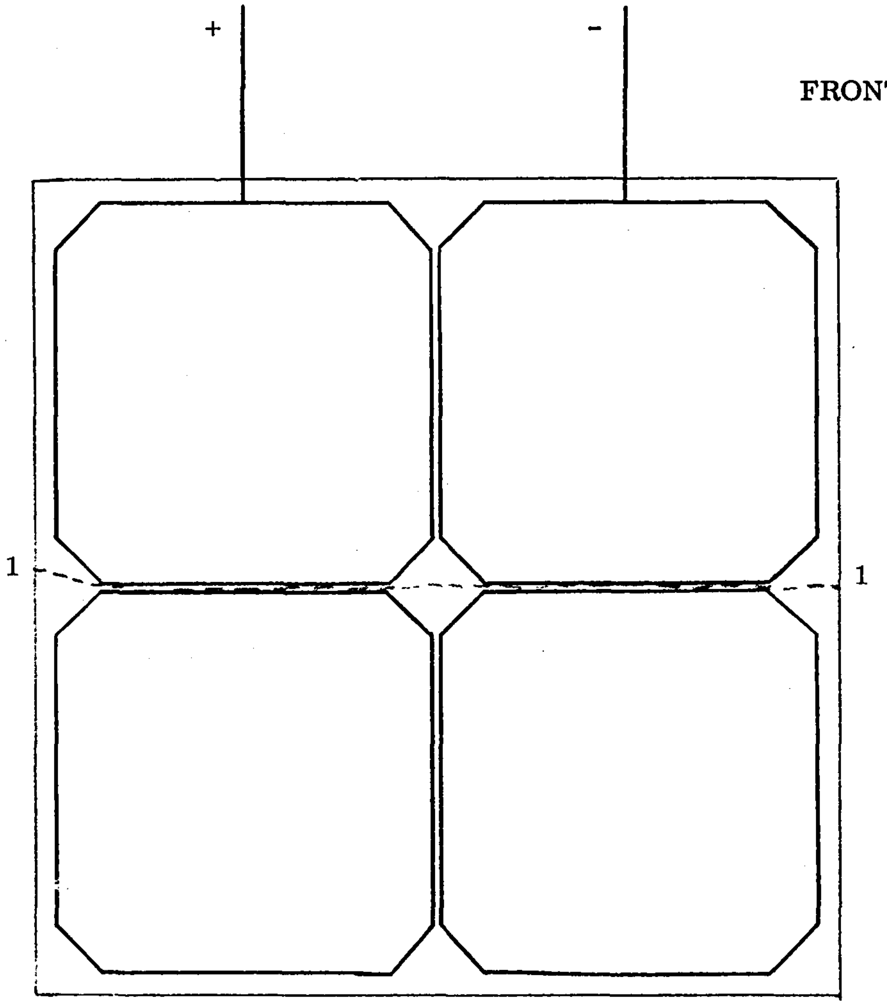


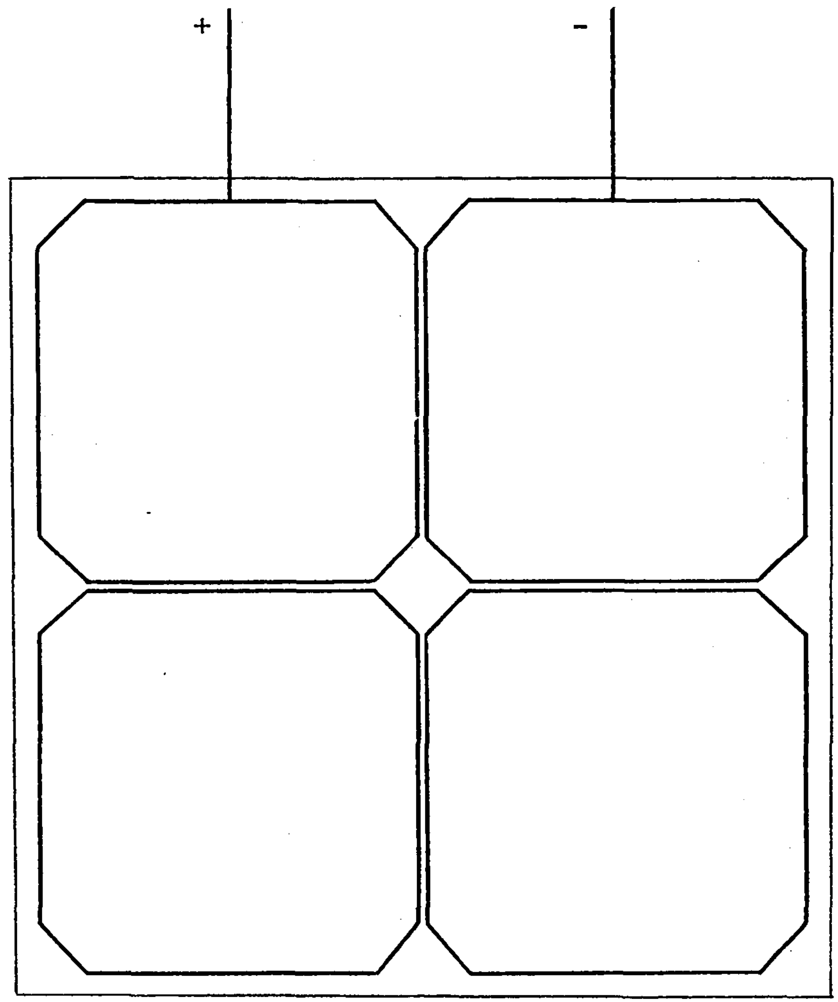
MODULE TYPE: STD CELLS

S/N: STD-M1
CONTROL MODULE-NON-TESTED

POST RAPID CYCLE WELD JOINT INSPECTION SHEET

FRONTSIDE





CELL TYPE: STD CELL

S/N: STD-M3

CELL TYPE: ____________

S/N: ____________

NOTE: — Solid lines indicate original cracks in superstrate prior to thermal cycling

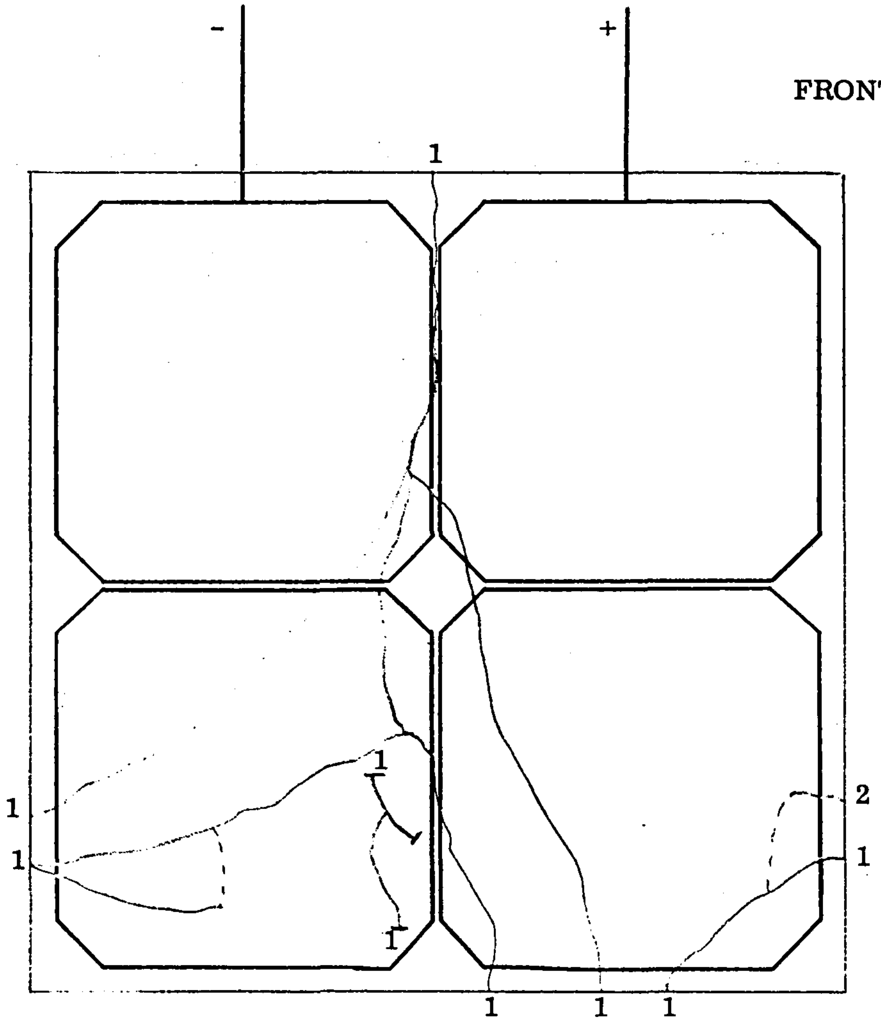
-- Dashed lines indicate cracks after 1060 cycles

Temperature Range: -73°C to +87°C

Cycle Time: 10 minutes

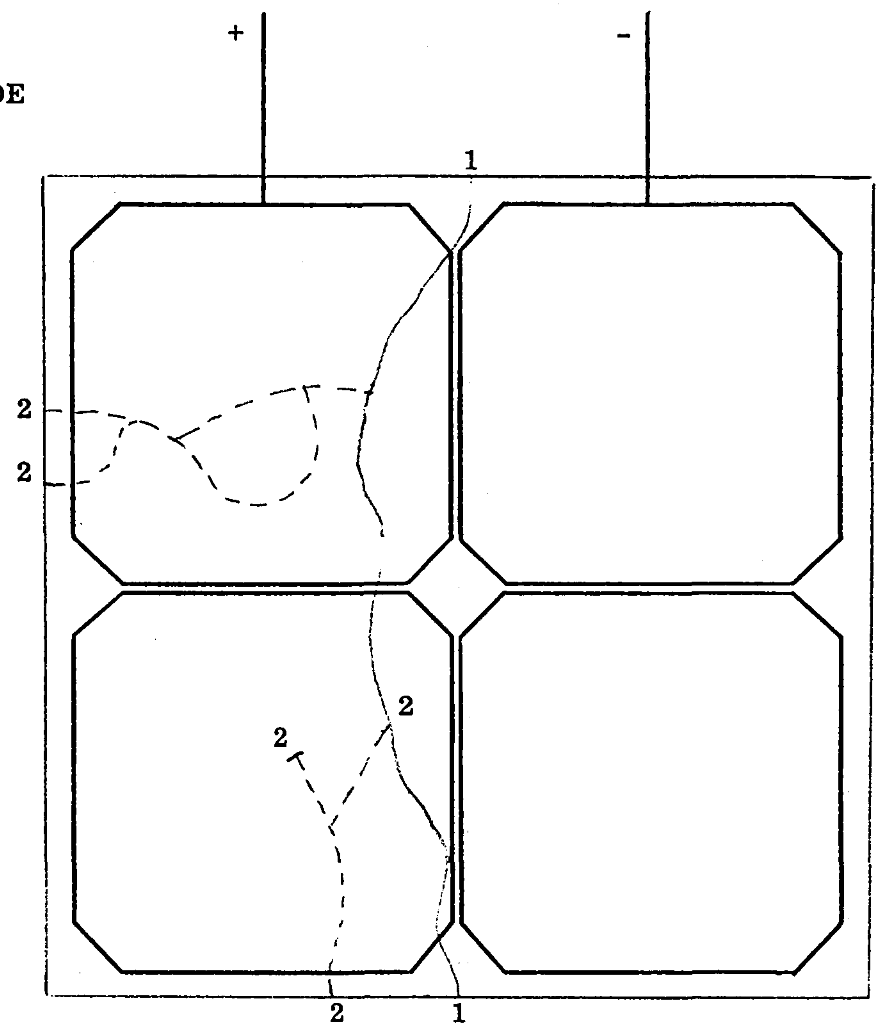
SUPERSTRATE INSPECTION SHEET

FRONTSIDE



MODULE TYPE: COPPER-SOLDERED NON-TESTED

S/N: CC-1



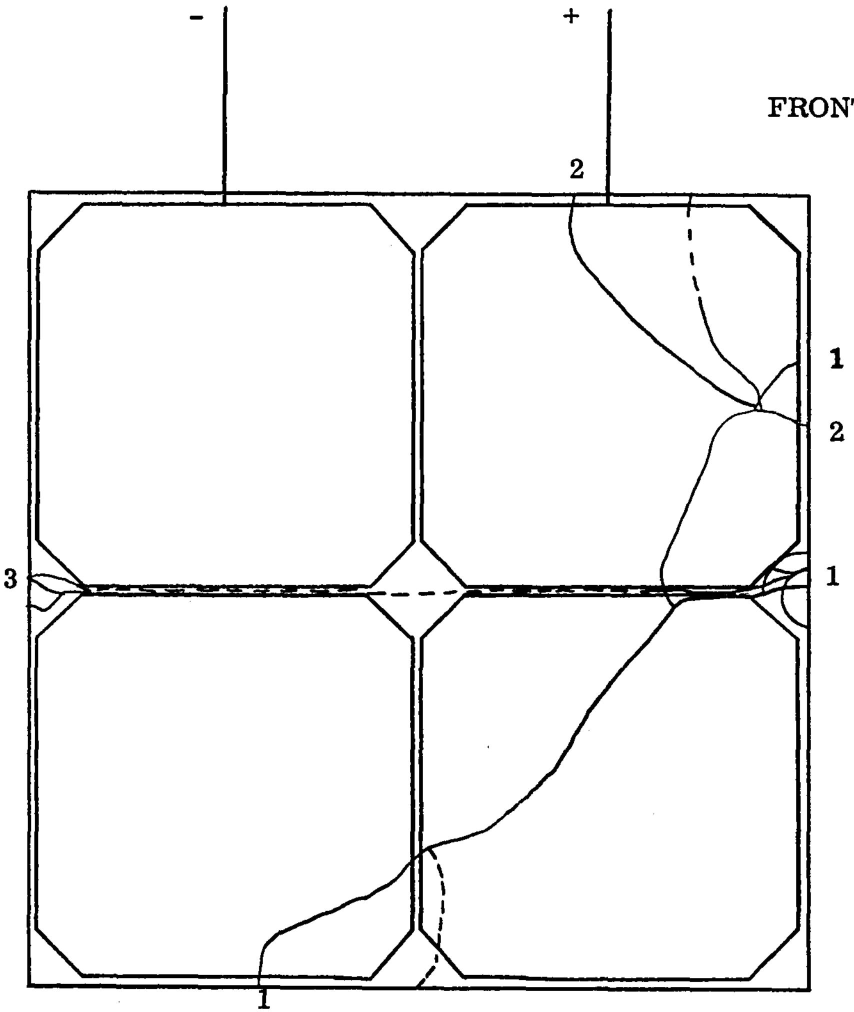
MODULE TYPE: COPPER-SOLDERED NON-TESTED

S/N: CC-2

NOTE: —— Solid lines - cracks noted after superstrate cure
--- Dashed lines - cracks noted after soldering operation

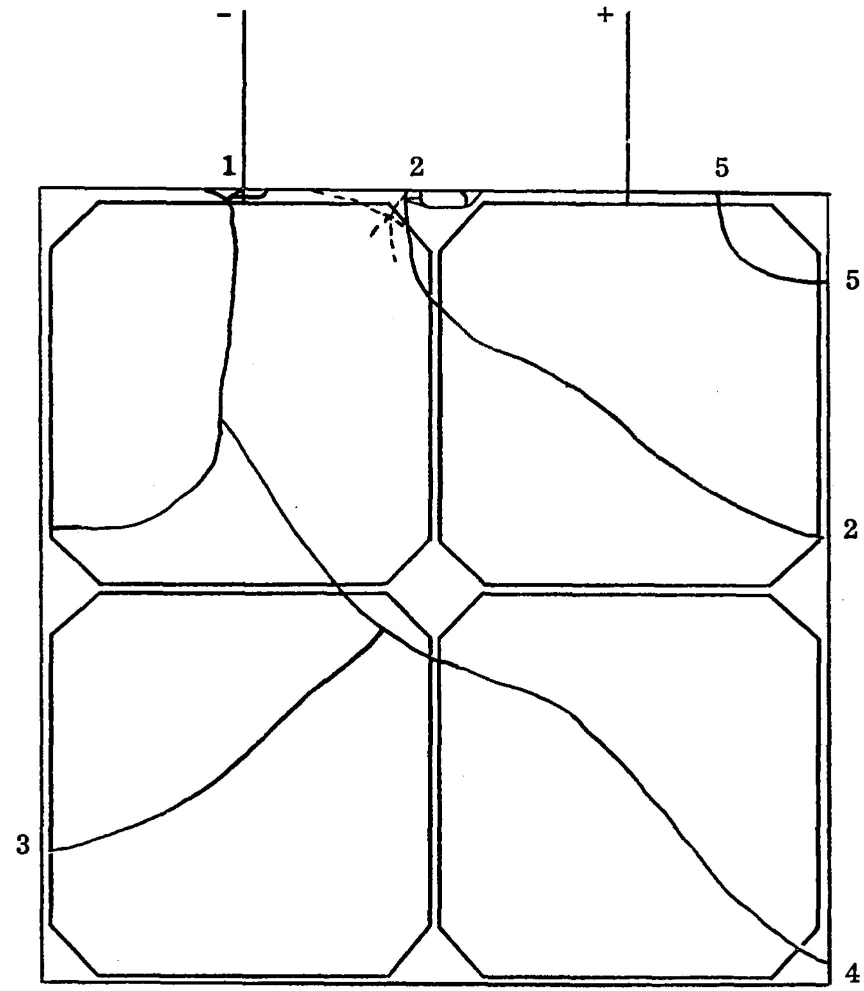
SUPERSTRATE INSPECTION SHEET

FRONTSIDE



CELL TYPE: GRIDDED

S/N: GĊ-M1



CELL TYPE: STD CELL

S/N: STD-M2

NOTE: —— Solid lines indicate original cracks in superstrate prior to thermal cycling

--- Dashed lines indicate cracks after 1060 cycles

Temperature Range: -73°C to +87°C

Cycle Time: 10 minutes

SUPERSTRATE INSPECTION SHEET

End of Document